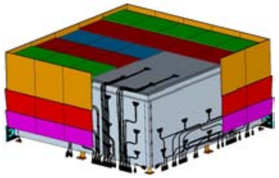

Development of Graphite Composite Blade Flexures for mounting of GLAST ACD Scintillating Tiles

by
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SWALES AEROSPACE

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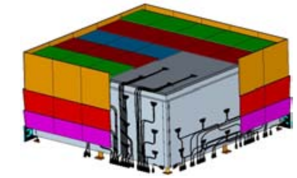
Acknowledgements



We would like to acknowledge many invaluable contributions from the ACD team and other NASA/GSFC and Swales colleagues including:

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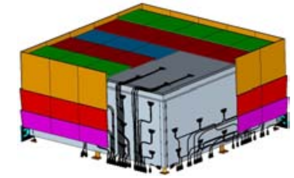
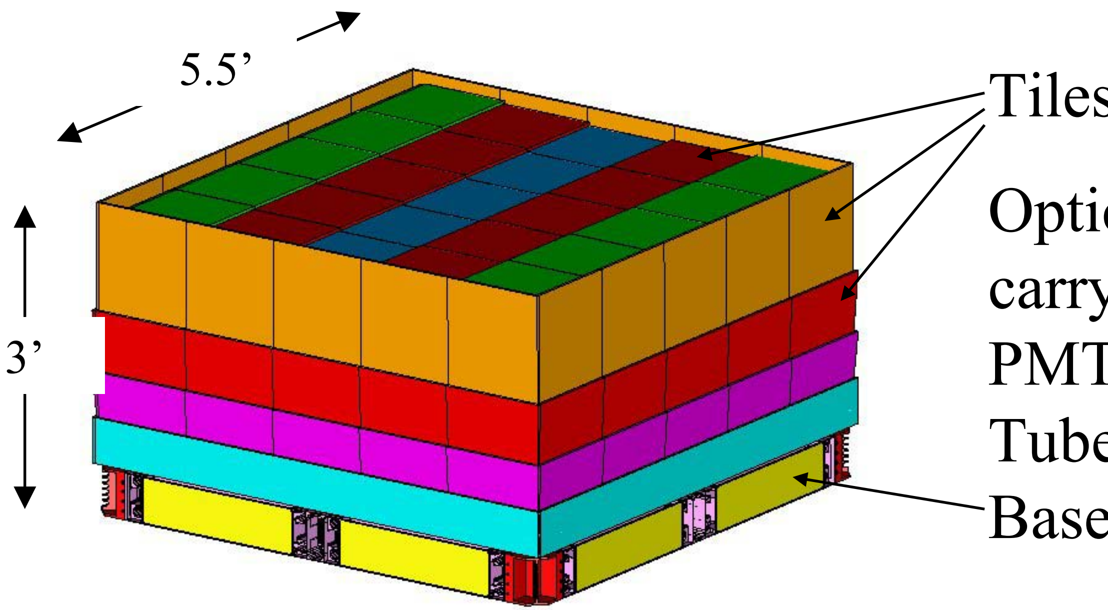
ACD Instrument Overview



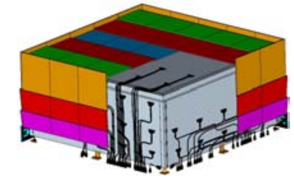
- ACD is part of the LAT Instrument of GLAST
- ACD is being developed and designed at NASA Goddard Space Flight Center.
- ACD surrounds the entire LAT field-of-view with Scintillating Tiles to detect Gamma Rays



Optical Fibers (not shown) carry signals from Tiles to PMT’s or Photo-Multiplier Tubes (not shown), housed in Base Electronics Assembly

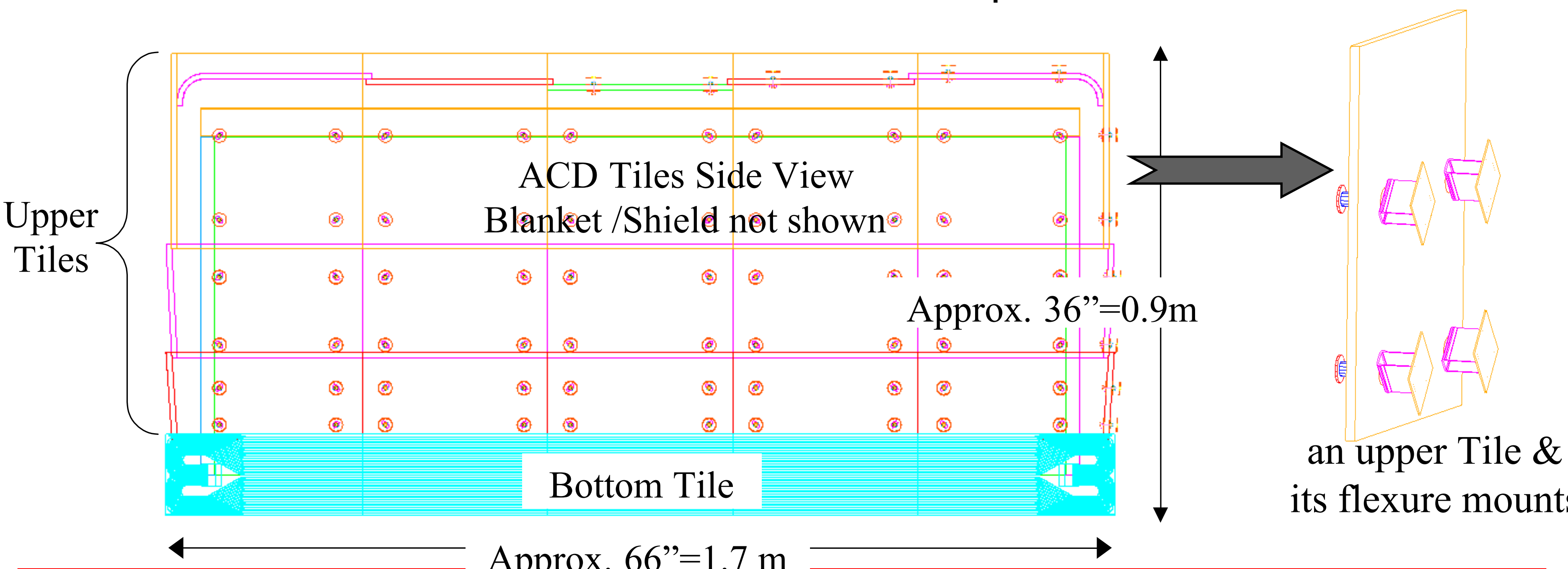
- ACD is entirely covered by a multi-layer Micro-Meteoroid Shield and a Thermal Blanket on the outside (not shown)

Presentation Overview

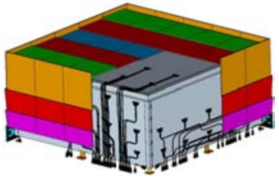


Presentation addresses:

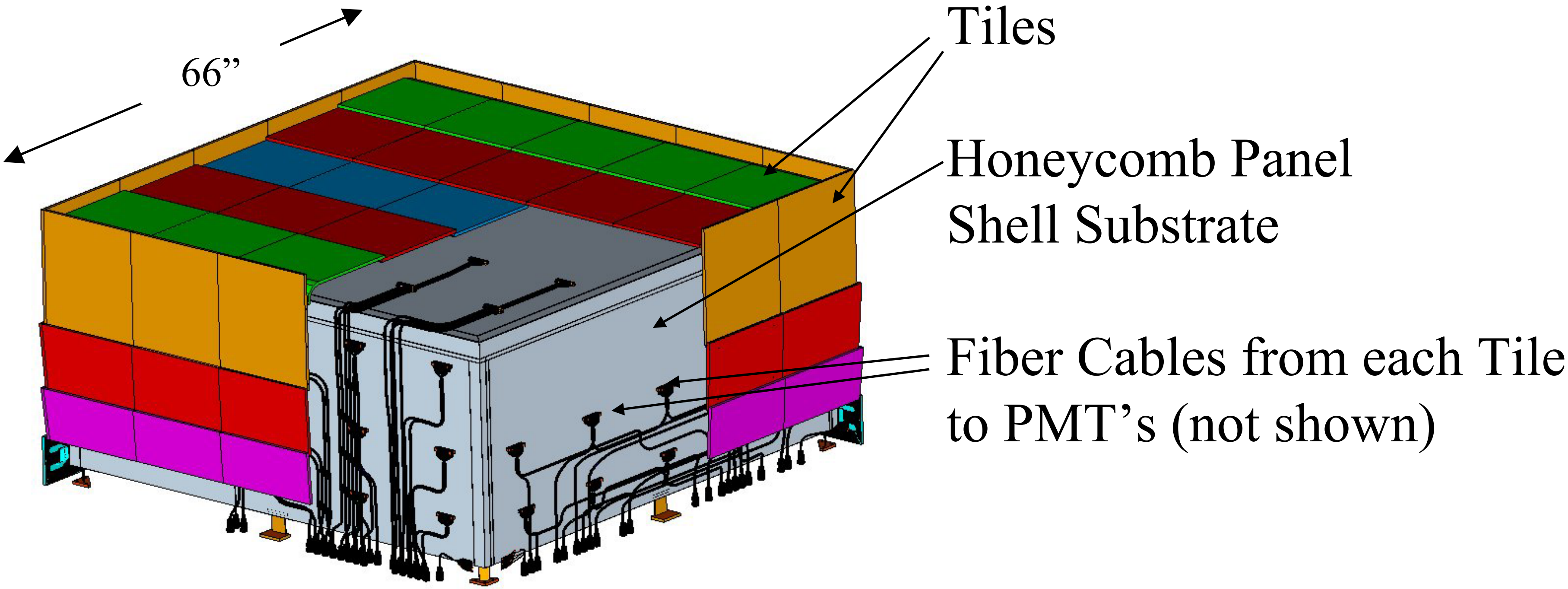
- the difficulties and challenging requirements associated with the mechanical mounting of the 85 Upper Tiles
- the final mounting design that meets the requirements
- Analyses & tests performed to come-up with the final design and to demonstrate that it meets the mechanical requirements



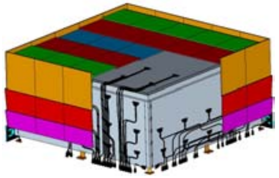
ACD Tile Detector Assemblies



- ACD has a total of 89 Tiles -not all shown below to reveal the shell substrate supporting the tiles and the optical fibers running from tiles to Photo-Multiplier Tubes (PMT's)
- TDA: Tile Detector Assembly consisting of a tile with its mounting hardware and optical fibers and connectors

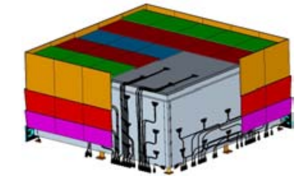


TDA Mechanical Requirements

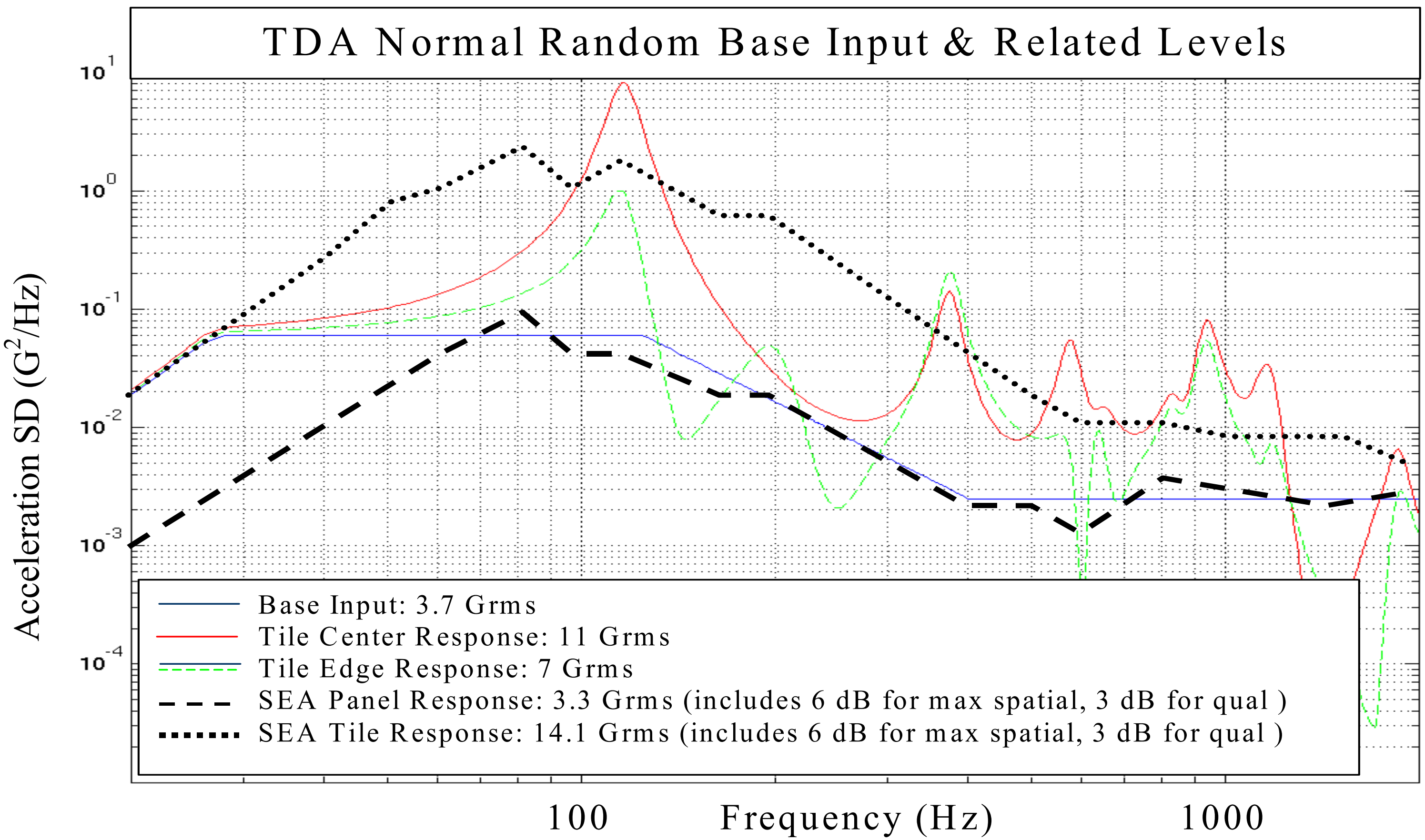


- Structural Integrity: Demonstrate positive Margins of Safety (MS) for all TDA's under all mechanical and thermal environments. Use the following Analysis Safety Factors (SF)
  - Tested Metallic Parts: 1.4 for ultimate and 1.25 for yield
  - Un-Tested Metallic Parts: 2.6 for ult and 2.0 for yld
  - Composite Material Parts: SF=1.5
- Fundamental Frequency: 70 Hz or greater
- Clearances: Minimize tile deflections under vibration and thermal loads so that gaps between the tiles can be on the order of 1 to 2 mm as needed by science.
- Extremely tight packaging requirements for TDA's and fibers
- Minimize the use of metallic components per science requirements.
- Service Life: No degradation of structural performance during the 5 years of orbital operation (design against fatigue, creep, wear)

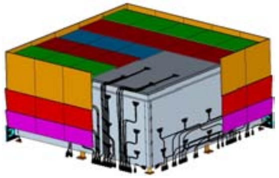
TDA Vibro-Acoustic Environment



TDA mechanical loads are driven by the acoustic environment outside ACD. Launch Vehicle Sound Pressure Level (SPL) spectrum is used in an Acoustic Statistical Energy Analysis (SEA) to determine acceleration spectral density (SD) of the tiles (SAI-TM-2177). These levels were used in the Tile Detector Vibration tests to qualify the TDA design.



Mechanical & Thermal Design Limit Loads



- Tile Quasi-Static Design Loads- 2 Cases: (applied separately)

  ±17 G out-of-plane of the tiles

  12 G in any lateral direction of the tiles
- Panels Quasi-Static Load Case

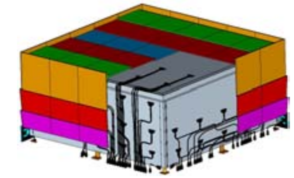
  ± 7 G in any direction

  Tile Deformations from this case to be combined with those from either Tile Load Case.
- Handling Loads: Limited to 10 LB at the blanket standoffs and 20 LB at the tiles.
- Extreme Temperatures of –45 C and +45 C (with ΔT=-65 C and +25 C)

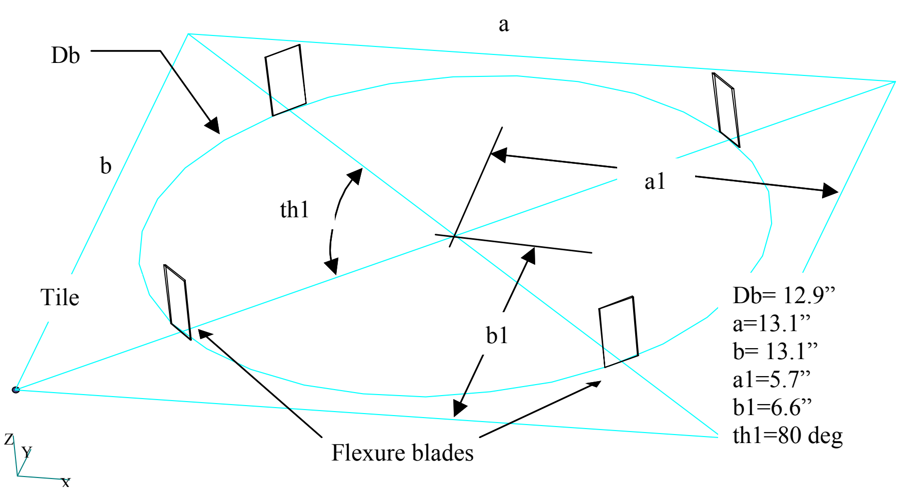
  Thermally induced motion wrt tile center is as much as 0.035”.

  Number of cycles = 12

Tile-Panel Interfaces

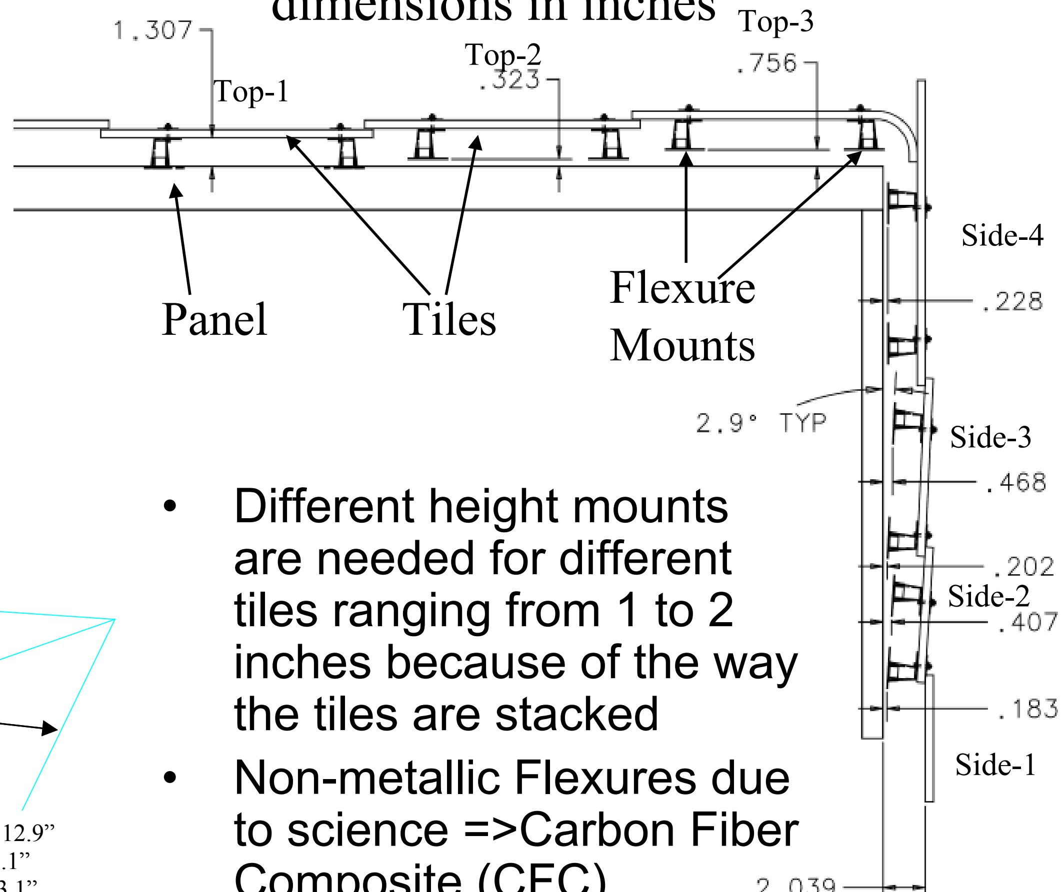


- In-plane kinematic interface needed to accommodate the thermally induced motion between the tiles and the panel substrate
- 4 Blade Flexures (~2-DOF mount) used per Upper Tile. 3 point mount was looked at but did not satisfy the stiffness requirements.



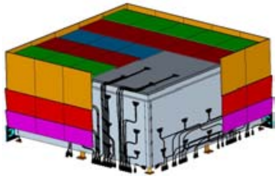
Typical Tile Mounting Arrangement

Sectional View of Tiles & Shell
dimensions in inches

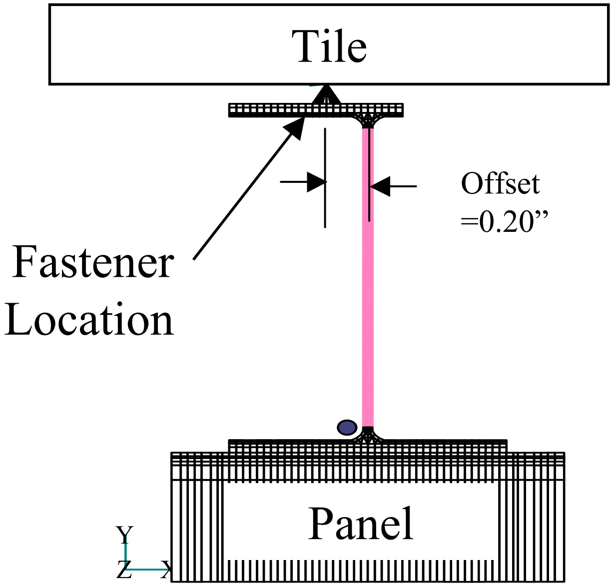


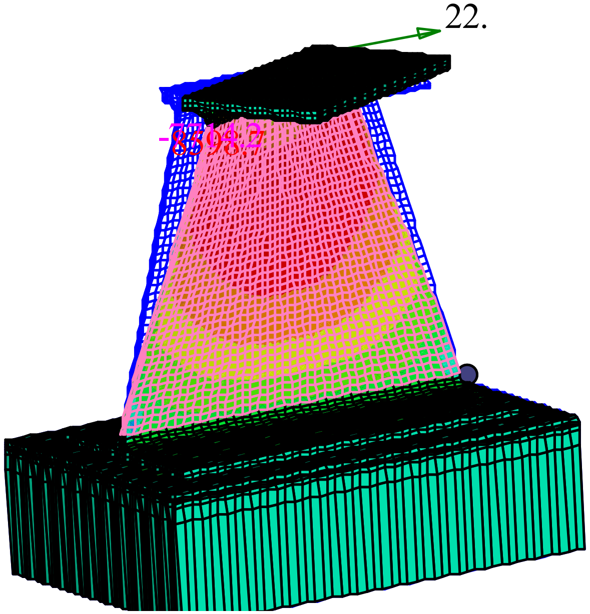
- Different height mounts are needed for different tiles ranging from 1 to 2 inches because of the way the tiles are stacked
- Non-metallic Flexures due to science =>Carbon Fiber Composite (CFC)

Flexure Design Development Single vs Double Blade



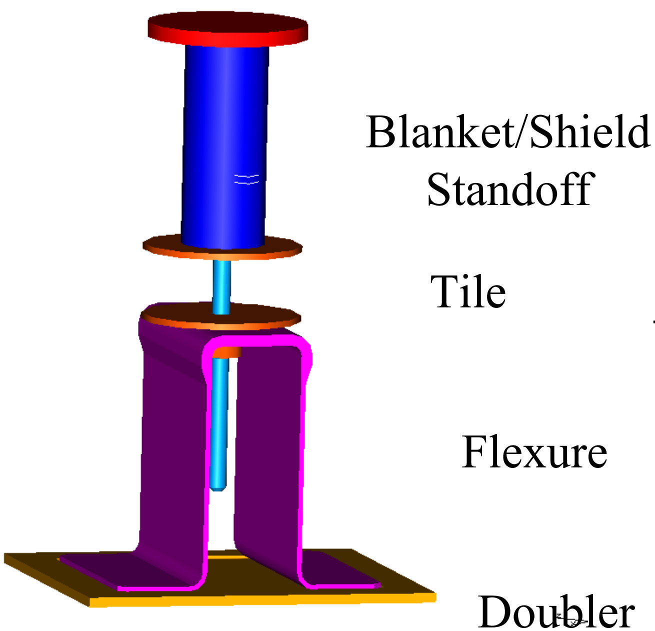
- Only one fastener per tile can be used due to science requirements.
- Single Blade Design with single fastener has a twist stability problem in the Strong Shear direction as illustrated below that led to unacceptably large tile deflections. Therefore, a double blade design was baselined for flight.

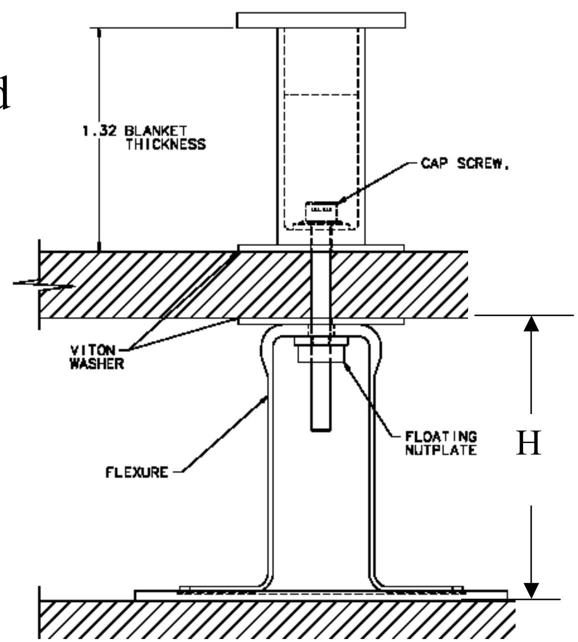


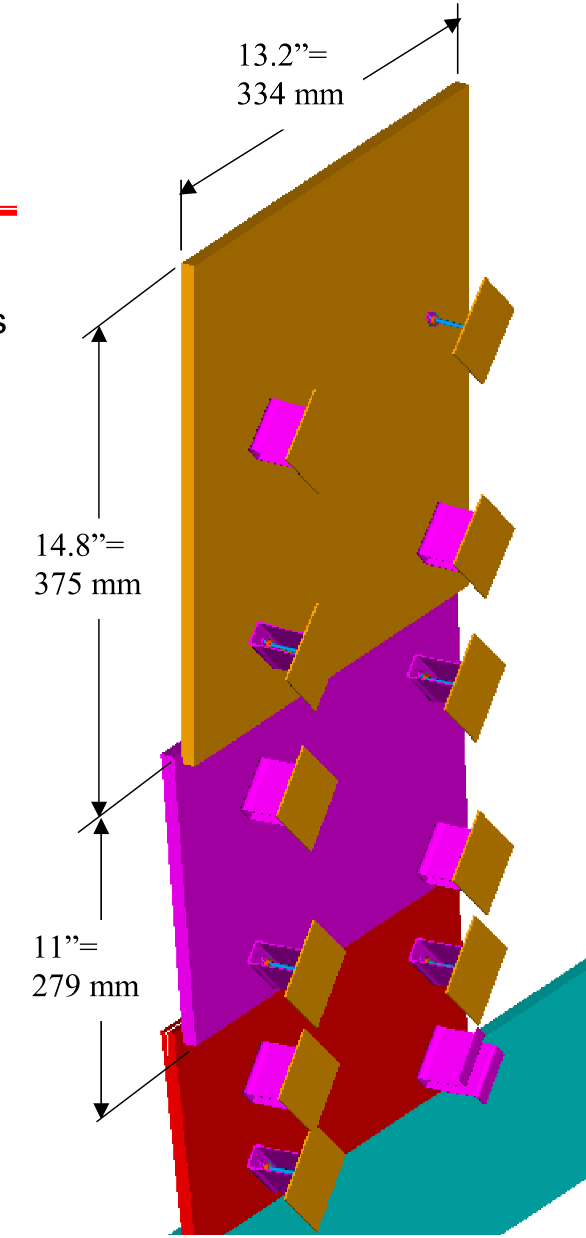


Tile Flexure Interface Flight Design

- Double Blade to prevent twist induced under strong axis load. Other Advantages: Limits thermally induced stress because of thinner blades and increases column buckling strength due to load sharing between blades and close to guided conditions at the tile end
- Single Fastener to Tile and Blanket/Shield Standoff
- Adhesively bonded to doubler on Honeycomb Panel
- No other local reinforcement in panel

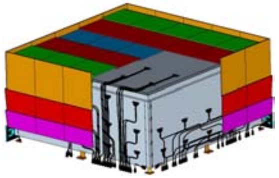




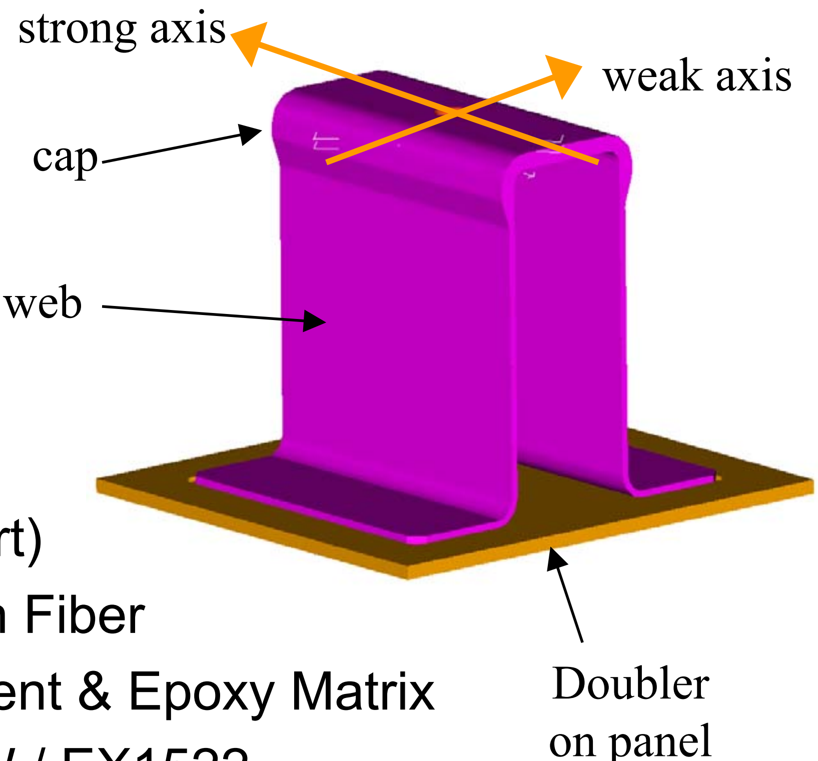


Side Tiles with Flexures

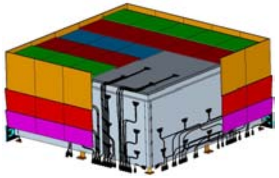
Flexure Material Selection



- Desirable Properties
  1. Low Modulus, Weak Axis
  2. High Strength, Weak Axis
  3. Good Bearing Strength
  4. Fatigue Resistance
  5. Compatible CTE with ACD Shell
  6. Ease of Fabrication (Shaped Part)
- Items 1 thru 5 suggest T300-Carbon Fiber
- Item 6 Suggests Fabric Reinforcement & Epoxy Matrix
- Final Laminate Selections: T300 PW / EX1522
  - Web: $[0_3/45/0_3]$ @ 35-mils Thickness
  - Cap: $[0_3/45/0_3]_2$ @ 70-mils Thickness

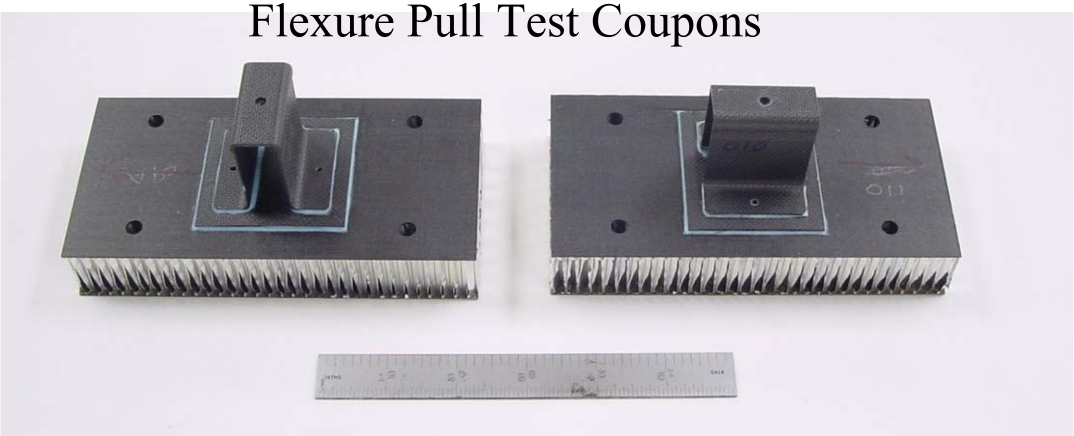


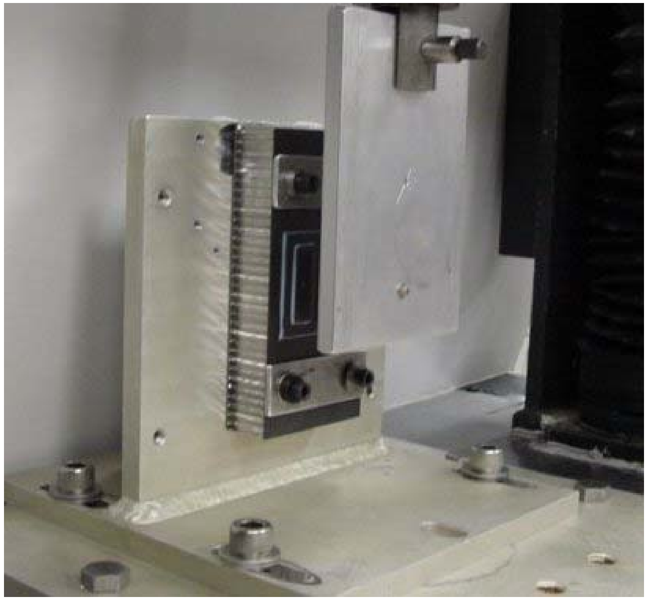
Flexure Characterization



- Material Acceptance Tests
- Doubler Laminate Mechanical Tests
- Flexure Laminate Mechanical Tests
- Flexure Consolidation
  - Photomicrographs
  - Web Mini-Beam-Specimens
  - Fiber Volume/Void Content
- Flexure/Interface Strength
  - Tension
  - Compression
  - Weak-Axis Shear
  - Strong-Axis Shear

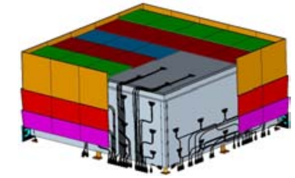
Flexure Pull Test Coupons





Flexure Pull Test Set-up (Strong Axis)

Flexure Material Properties

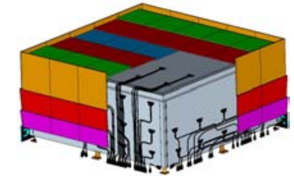


- Initial Ply Values Based on Literature Results and Micro-mechanics
- Laminated Plate Theory for Flexure Laminate
- Adjustments of Ex, Ey, σ_{FLEX} using Test Data from Mini-Beams from Flexure Webs & Caps
  - Modulus by Acoustic Resonance
  - Strength by 3 Point Flexure
- 3-D Lamination Theory for 3-D Stiffness Values (Chou, Carleone, and Hsu, “Elastic Constants of a Layered Media,” J. Comp. Mat’ls, Jan.1972)

Flexure Mini-Beam Results

Laminate I.D.	E_X		σ_{FLEX}		Remarks
	Avg. (msi)	COV (%)	Avg. (msi)	COV (%)	
TF-001	7.52	3	99.8	6.5	T300/EX1522, Web
TF-011	7.8	0.5	139.1	1.3	T300/M76, Cap
TF-028	8.0	2	97.9	2.7	T300/EX1522-2, Web

TDA Structural Analyses & Correlation Outline



Flexure Detailed FEA

Tile FEA
using simplified Flexure Representations

Flexure Pull Tests
Correlate Flexure Stiffness & Strength

TDA Vibe Tests
Demonstrate TDA Strength & Workmanship
Correlate Deflections

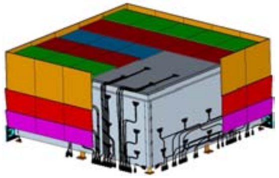
Finalize Strength & Stiffness Sizing of all the other flight Flexures using correlated Flexure FEM

Demonstrate by Analysis that all flight Tiles meet Stiffness & Strength Requirements

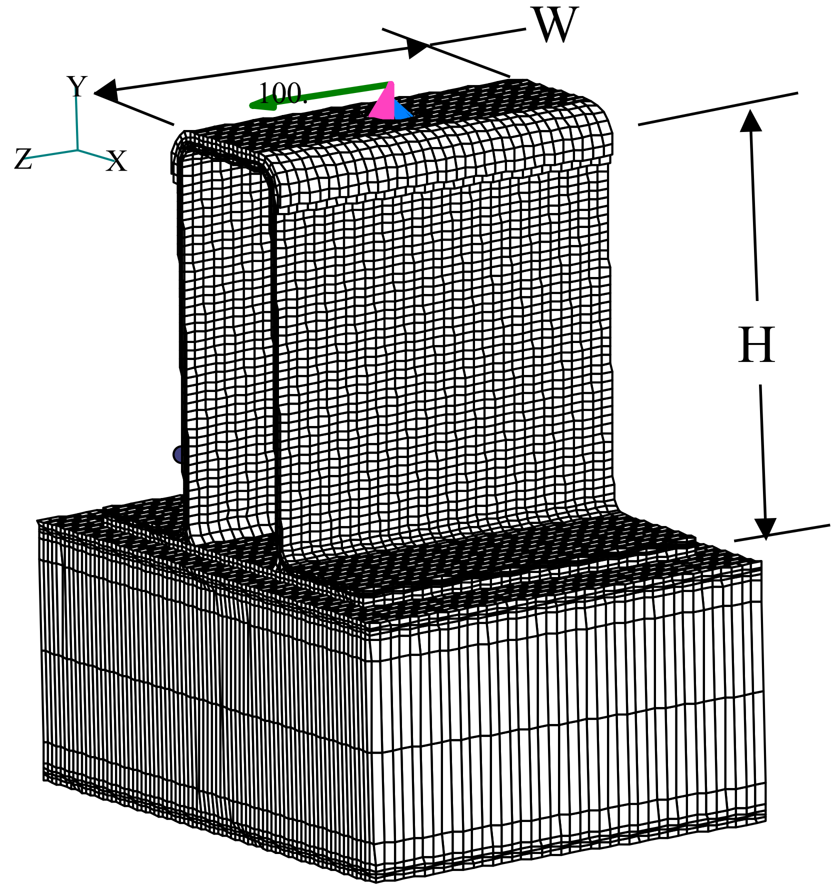
Acceptance Testing of Flight TDA's

Status: All Analyses, Testing & Correlations complete except Flight Acceptance Testing.

Flexure Detailed FEA
For Stiffness & Stress Analysis

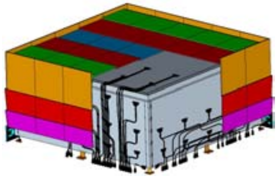


- Detailed FEM (74,000 nodes) to capture stress peaking in critical bonded and radius areas
- Flexure FEM Properties:
  T300 Plain Weave [0_3/45/0_3]
  Ex=Ey=7.8 msi, Gxy=1.12msi
  Blade Wall Thickness = 0.035”
  Flexure Height, H=1.6”
  Flexure Width, W= 1.5”
  Doubler Thickness= 0.040”
  Blade Spacing=0.55”
  Fillet Radii= 0.060”
- Load Cases:
  Strong Axis Shear (shown)
  Weak Axis Shear
  Tension/Compression

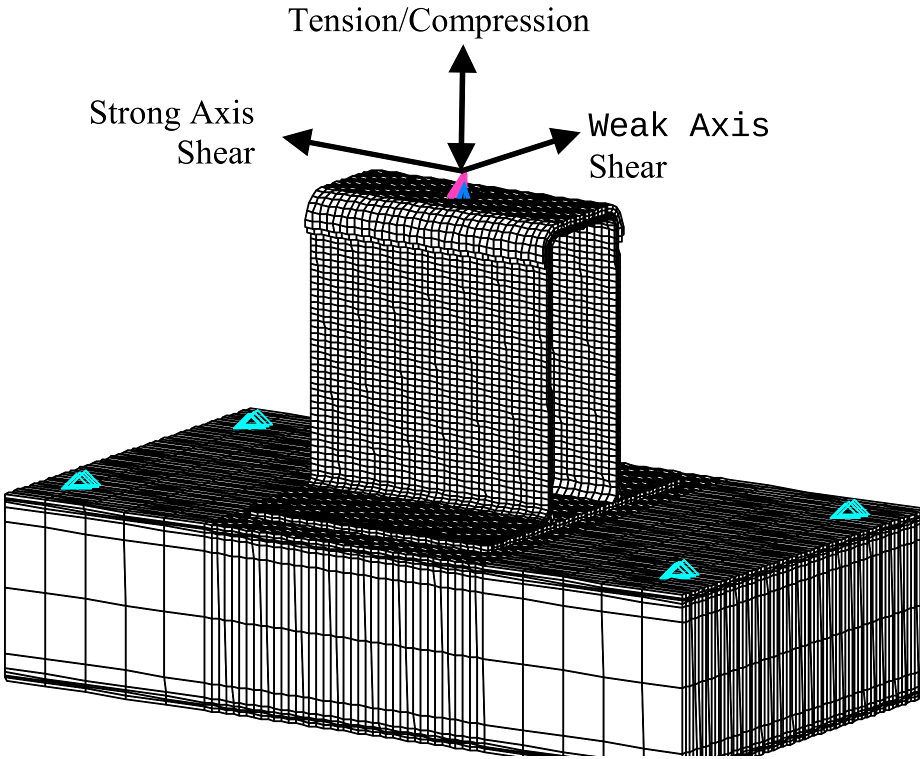


- 4 different flexure FEMs generated and used for stiffness and strength analysis. They only differ in height and thickness of panel they are bonded to.

Flexure Pull Tests & Correlation

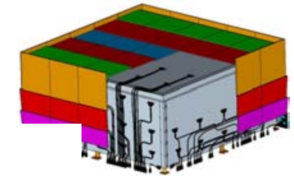


- Flexure samples tested in Tension, Compression, Weak and Strong Axis Shear (3 samples x 4 axis=12 tests) on 2" thick honeycomb panel constrained at 4 bolt locations.

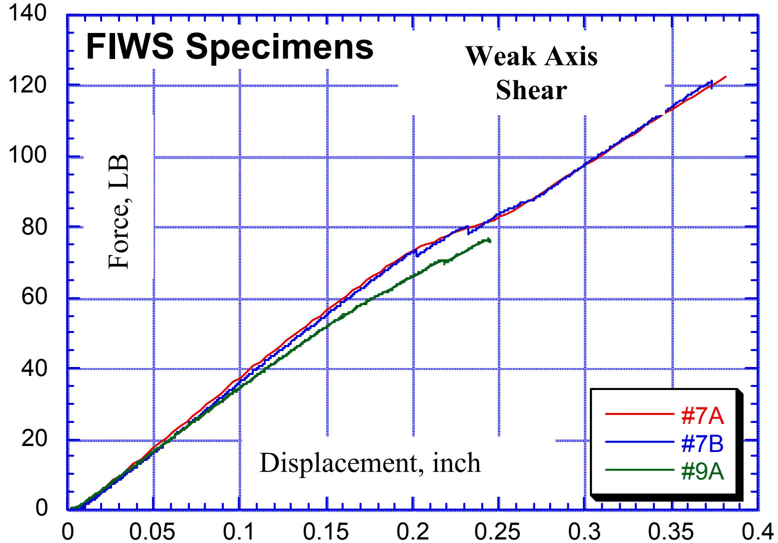


- Results consistent and repeatable
- Strength Allowables much higher than static design limit reactions
- Detailed FEA results successfully correlated with test results.

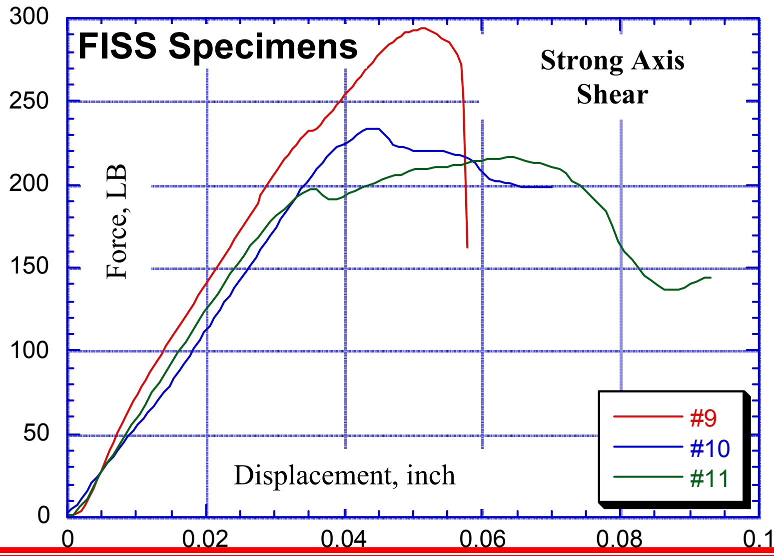
Summary of Flexure Pull Test Results

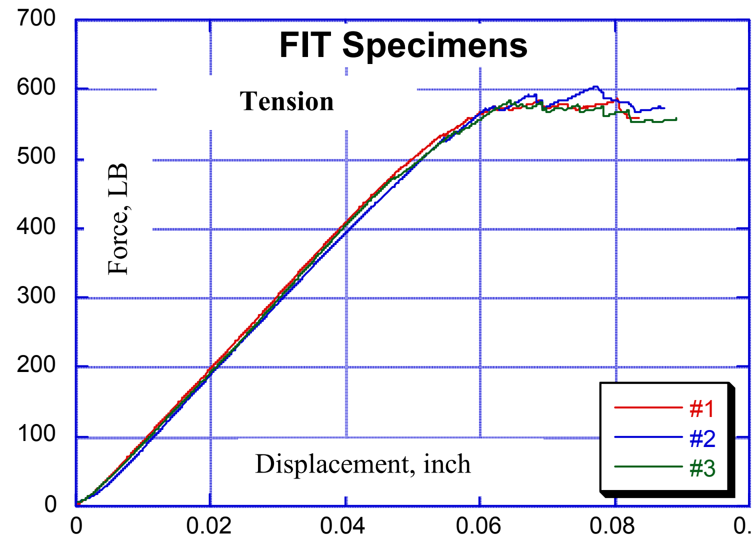


Flexure Pull Test Results Summary

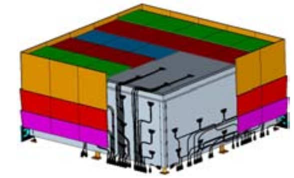


	Stiffness LB/in	Ult. Strength LB	Ult. Disp. inch	Failure Mode
Weak Axis Shear	340	70	0.206	Upper & Lower Flange delam
Strong Axis Shear	6250	200	0.032	Lower Flange delam
Tension	10600	550	0.052	Top Flange Bending
Comp-ression	54550	1000	0.018	Buckling & Core Crushing

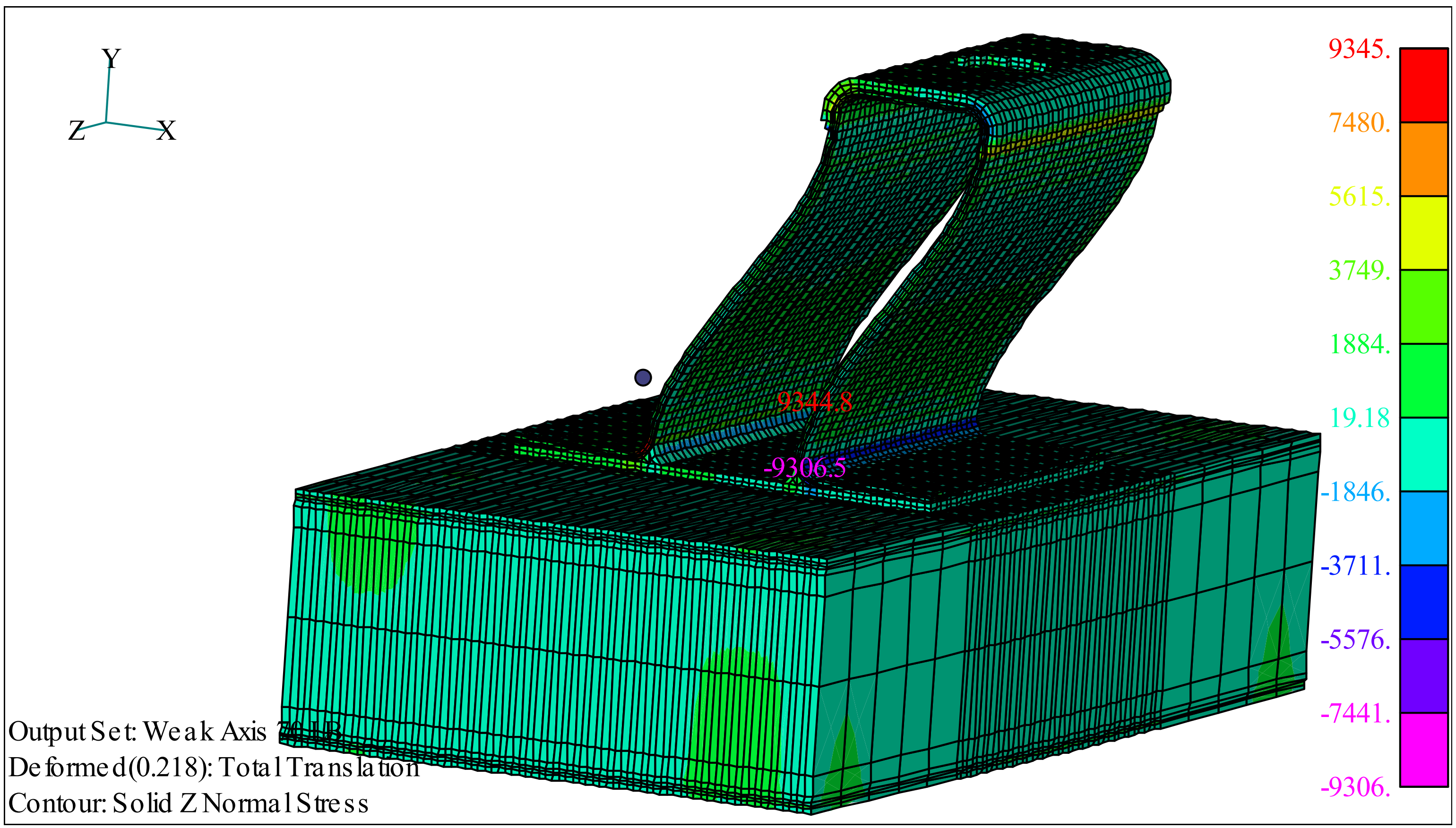




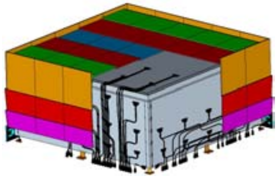
Flexure Stiffness & Strength Correlation under Weak Axis Shear

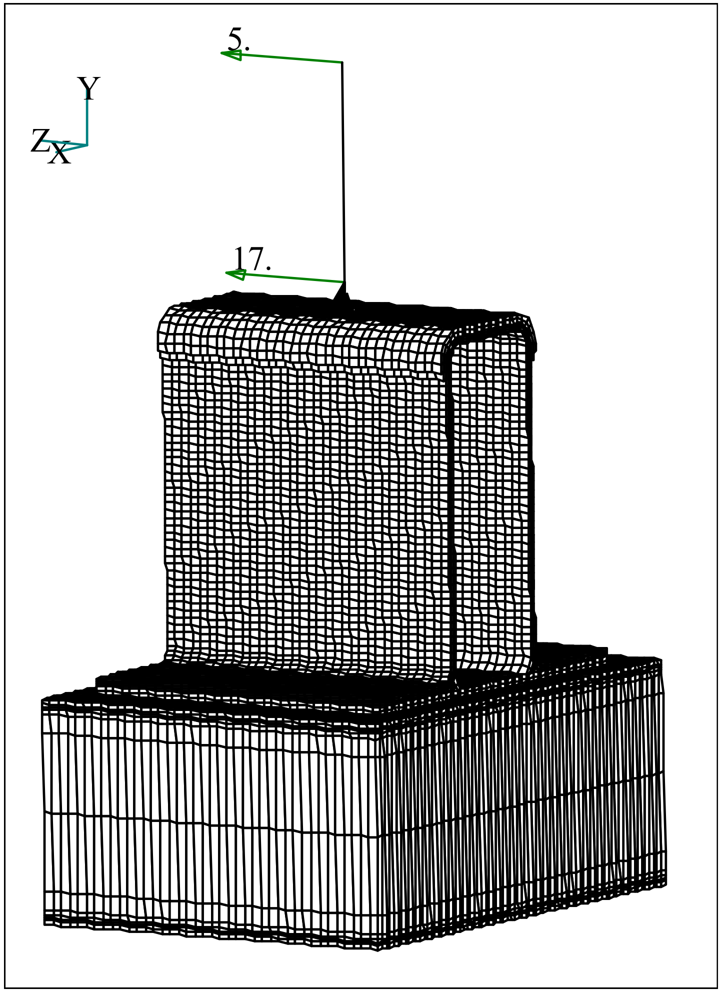


Under 70 LB weak Axis Shear (Test Failure Load)
Peel stresses exceed 9 ksi to cause failure in agreement with pull test results.
Stiffness=70/.218=320 Lb/inch (6 % less than measured)



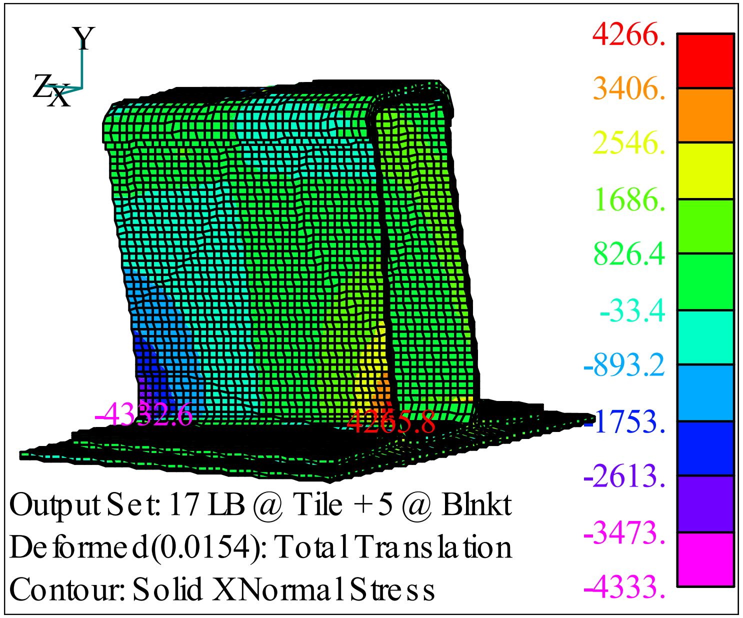
Flexure Stress Analysis under Strong Axis Shear

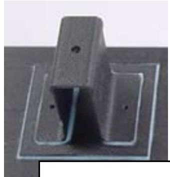




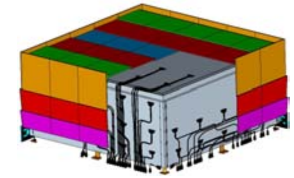
Shear Loads applied at the blanket/shield centroid and at the tile interface

Flexure Laminate
in-plane 0 º Direction Stresses (psi)

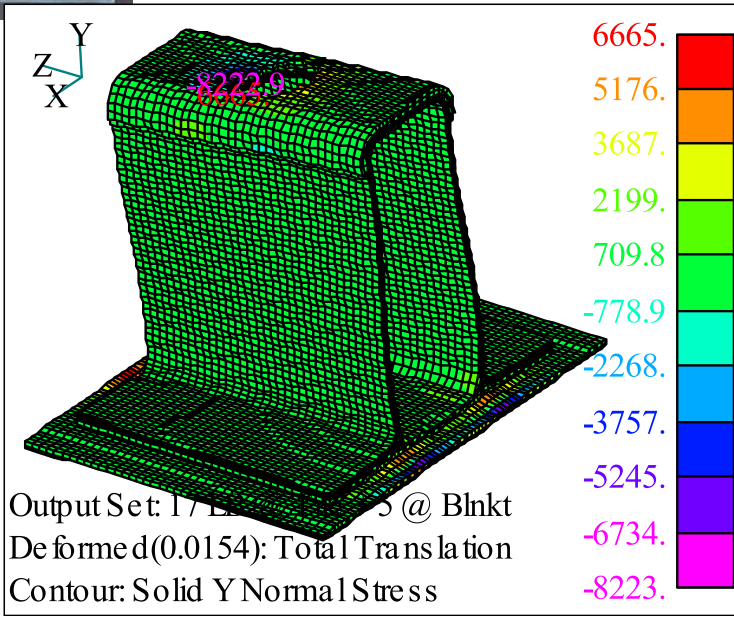




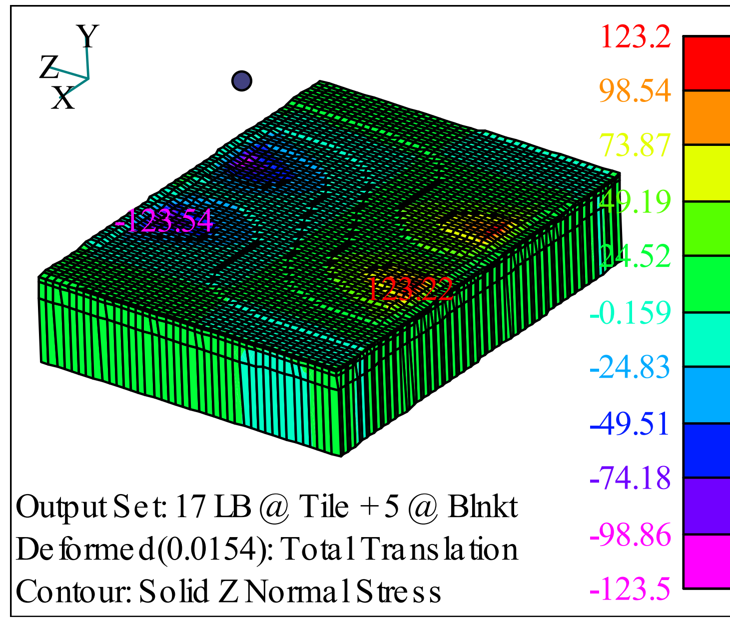
Flexure Stress Analysis Strong Axis continued

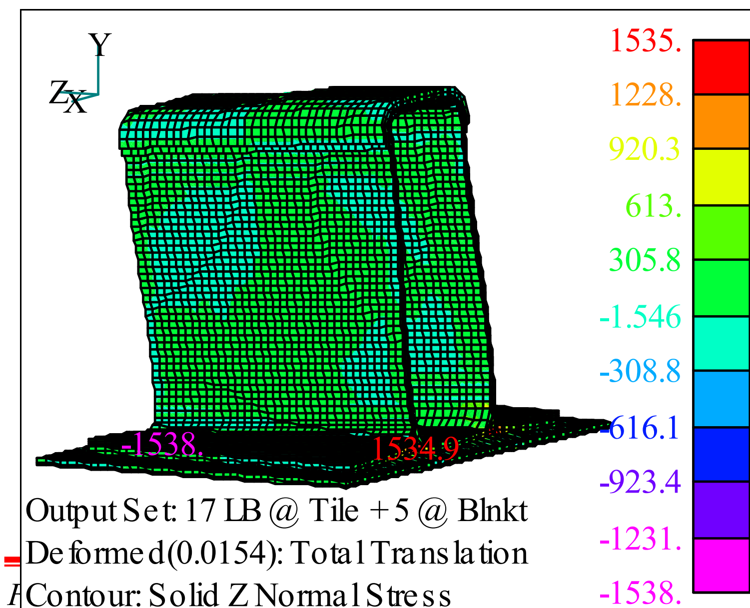


Flexure Laminate 90º direction stresses (psi)



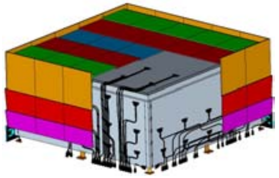
Core Compressive Stresses (psi)



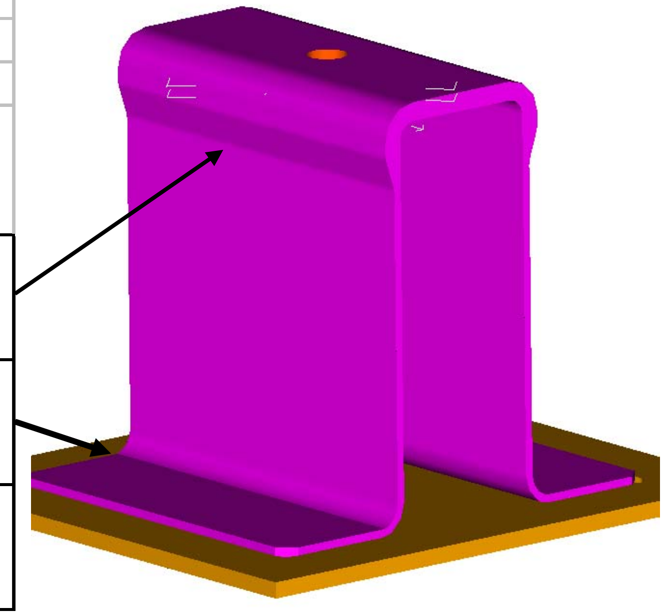


Flexure Laminate peel stresses (psi)

Flexure Stress Analysis Summary

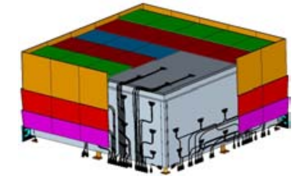


	Sumary of Flexure Stresses & Margins				
using ultimate SF=		1.50			
Case	Loading	Failure Mode	Critical Stress psi	Allowable Stress psi	MS
1	Thermally Induced motion of 0.035"	Lower Radii or Cap	3300	8000	0.62
2a	Strong Axis Design Limit Shear+Bending	Lower Flange Delam	1540	8000	2.46
2b		Core Crushing	123	360	0.95



- All Flexure MS are high under static design limit loads.
- Sustained stress and fatigue under operational thermal environment should not be a problem owing to the high MS under static design limit loads.

Composite Flexures Observations & Discussion

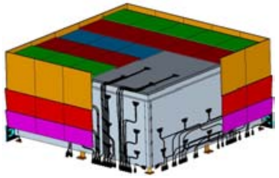


- Carbon Fiber Composite (CFC) Flexures met the stiffness and static strength requirements of this application with ample margin.
- The CFC laminate strength and stiffness properties were tailored for a blade flexure, i.e.; high ratio of strength to stiffness (Ft/E) as evidenced by the following comparison with other typical flexure materials:

Material	Strength Ft, ksi	Elastic Modulus E, ksi	Ft/E *1000	Notes
Ti-6Al-4V (Titanium Alloy)	130	16,000	8.1	
C17200 (Copper-Beryllium)	137	18,600	7.4	low elongation
SS-17-4/H1150 (Stainless Steel)	115	28,500	4.0	
T300/EX1522 (Tile Flexure Laminate)	73	7,800	9.4	provided full strength can be developed low elongation

- However, it should be pointed out that the above comparison is fair only if the full strength of the CFC laminate can be developed and not limited by material inter-laminar failure.
- The strength of this CFC flexure design is limited by the interface strength of the adhesively bonded areas especially in the strong axis direction (hence limited launch load capability)
- In using composite laminates for flexure applications, it is very important to:
    - improve and verify the interface strength of composite laminates
    - keep stress concentration areas under control since material is not as forgiving due to low elongation capability
    - verify the fatigue strength especially for cases involving “a lot of” cycles or “high” stress amplitudes

Tile FEA Overview



- Used for predicting:

1- Tile Normal Modes, and Frequencies,

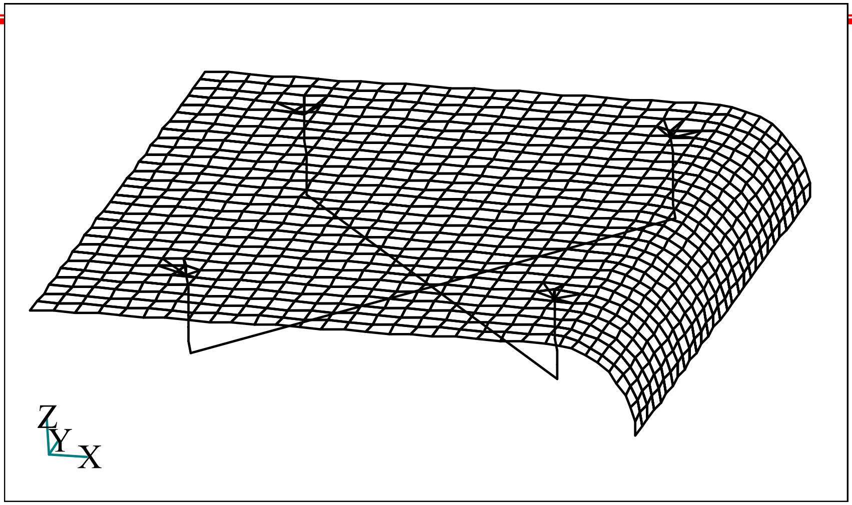
2- Tile Deformations and under Inertial and Thermal Loads

3- Flexure and Interface Reaction Forces, Tile Stresses under Mechanical and Thermal Loads

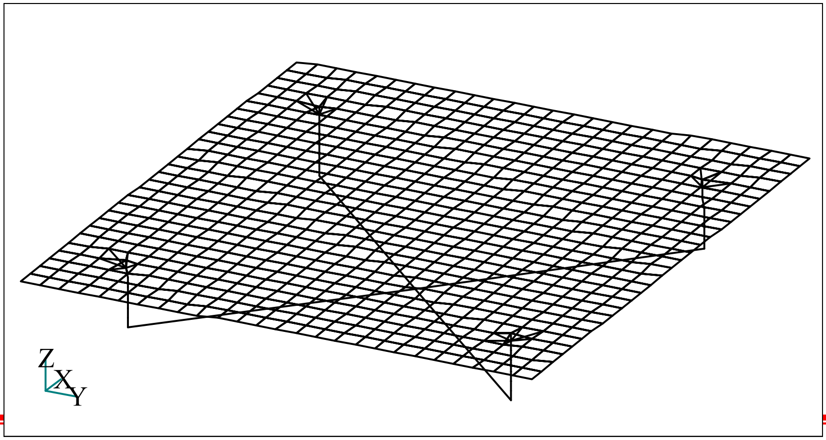
- Tile FEM validated by modeling the TDT configuration and correlating the vibe test and FEA results.

- Performed and passed FEM checks.

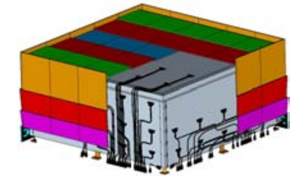
- 6 different FEMs are generated and used to simulate different flight tile designs.



2 different Tile FEMs
(See through views and no Mass elements for clarity)



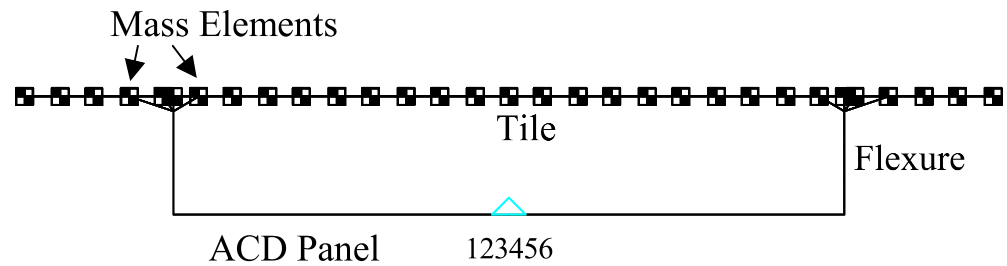
Tile FEM Assumptions



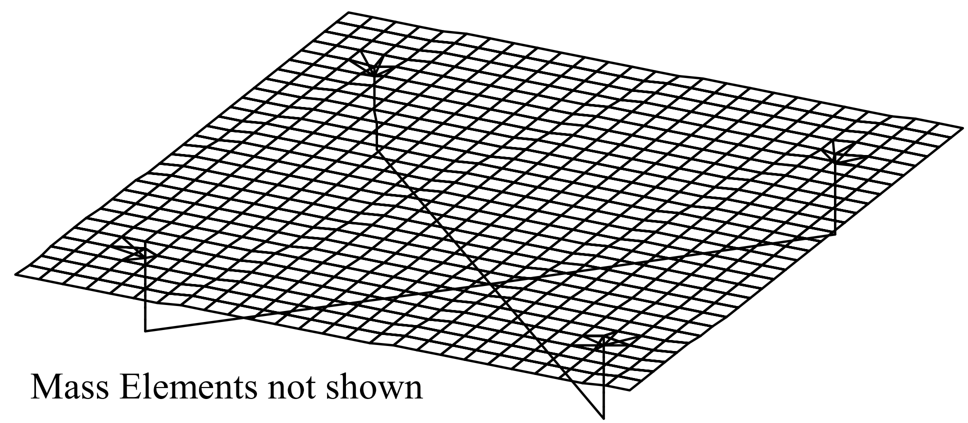
- Simple TSA panel representation to simulate thermal loading. ACD panel flexibility ignored here and accounted for elsewhere. Thermal motions take place wrt the flexure center on TSA panel , where the constraint is.

- Tile modeled by plate elements.

•Flexures modeled as bar elements. Bar element properties based on off-line detailed FEA correlated with pull test results.

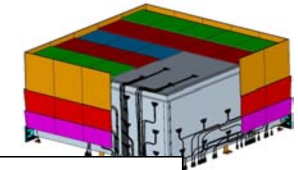


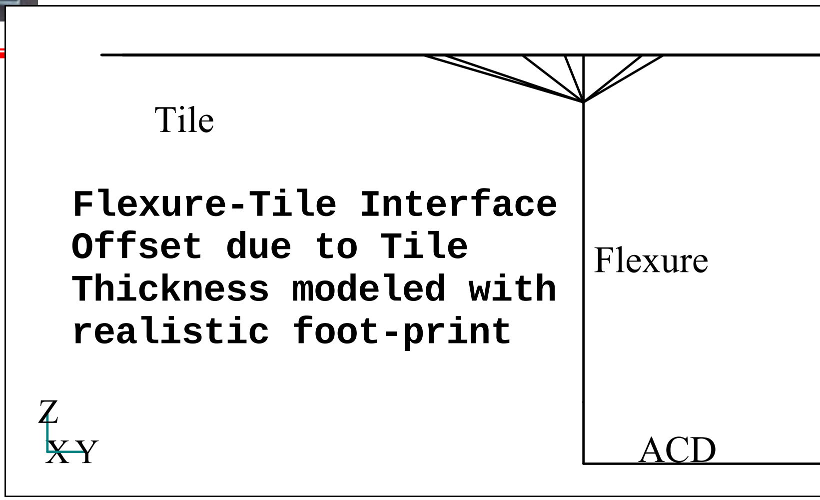
Typical Tile FEM Views

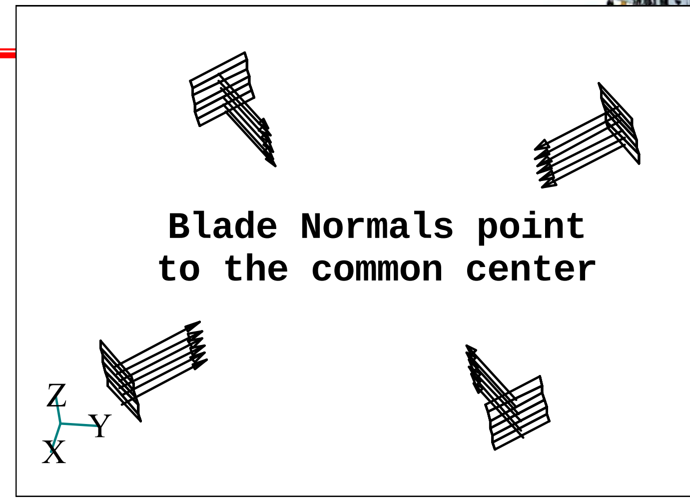


- Mass elements represent shield/blanket weight and are offset to the upper surface of the tile. Mass elements that are on the flexure tops simulate the effect of in-plane loading. Mass elements distributed on the rest of the tile represent the out-of-plane loading.

Tile FEM Assumptions & Properties



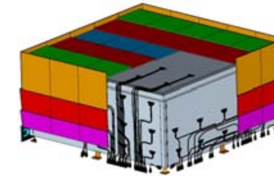




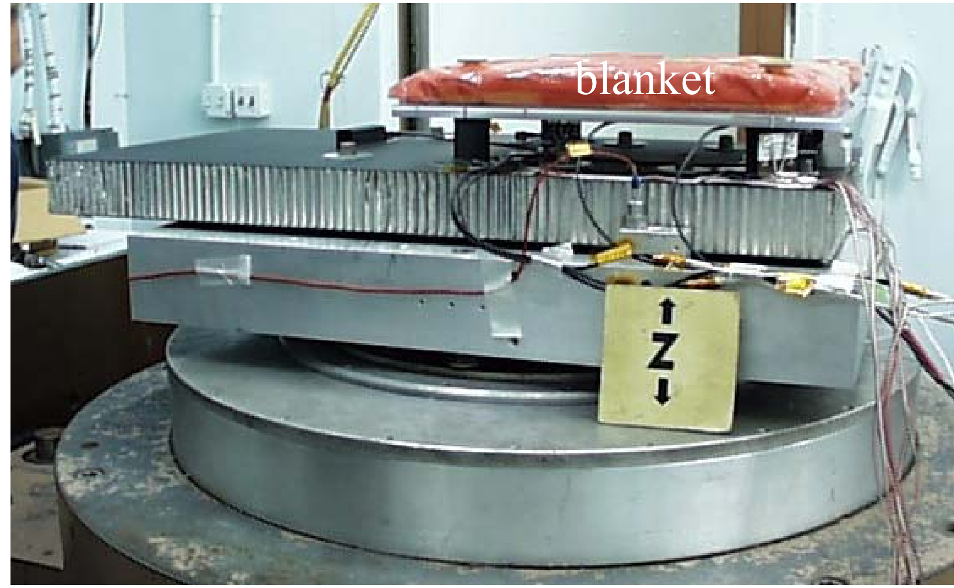
Material Properties used in Tile FEA				
	Young's	Poisson's	CTE	Density
	Modulus	Ratio	ppm/C	LB/in^3
Material	psi			
Tile (BC408)	415,000	0.3	78.0	0.04
Flexures	7.80E+06	0.3	0.2	0.06
Shell Representation	1.40E+07	0.3	1.0	N/A

Tile FEMs used the following weights + 10% contingency.						
	Tile and Blanket Weights					
Tile	Top-1	Top-2	Top-3	Side-2	Side-3	Side-4
Tile Weight,LB	2.4	2.4	2.7	1.1	1.4	2.5
Blanket/Shield Weight, LB	0.72	0.72	0.81	0.33	0.42	0.75

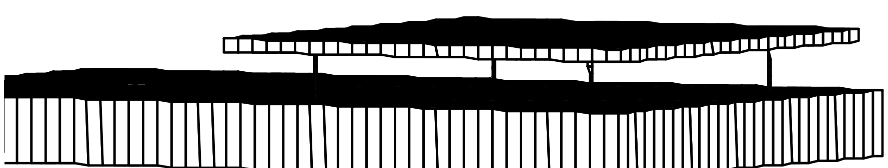
Tile Detector Vibe Tests & Correlations



- Sine Burst, Random Vibe, and Sine Sweep Signature Tests in Normal and Lateral directions to qualify the mechanical design.
- FEM updated and tuned based on test results.
- Analysis & test Fundamental frequencies agree within 10%
- A correction factor of 1.5 applied to analysis out-of-plane deflection predictions to match test
- Test in-plane deflections are "large" and explained by oversized tile fastener holes



TDT FEM



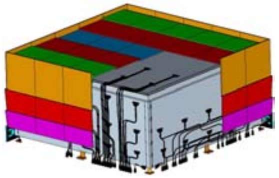
Sine Burst Levels determined to induce 1.25 times the max limit flight flexure reactions:

Normal: 36.5 G (Z)

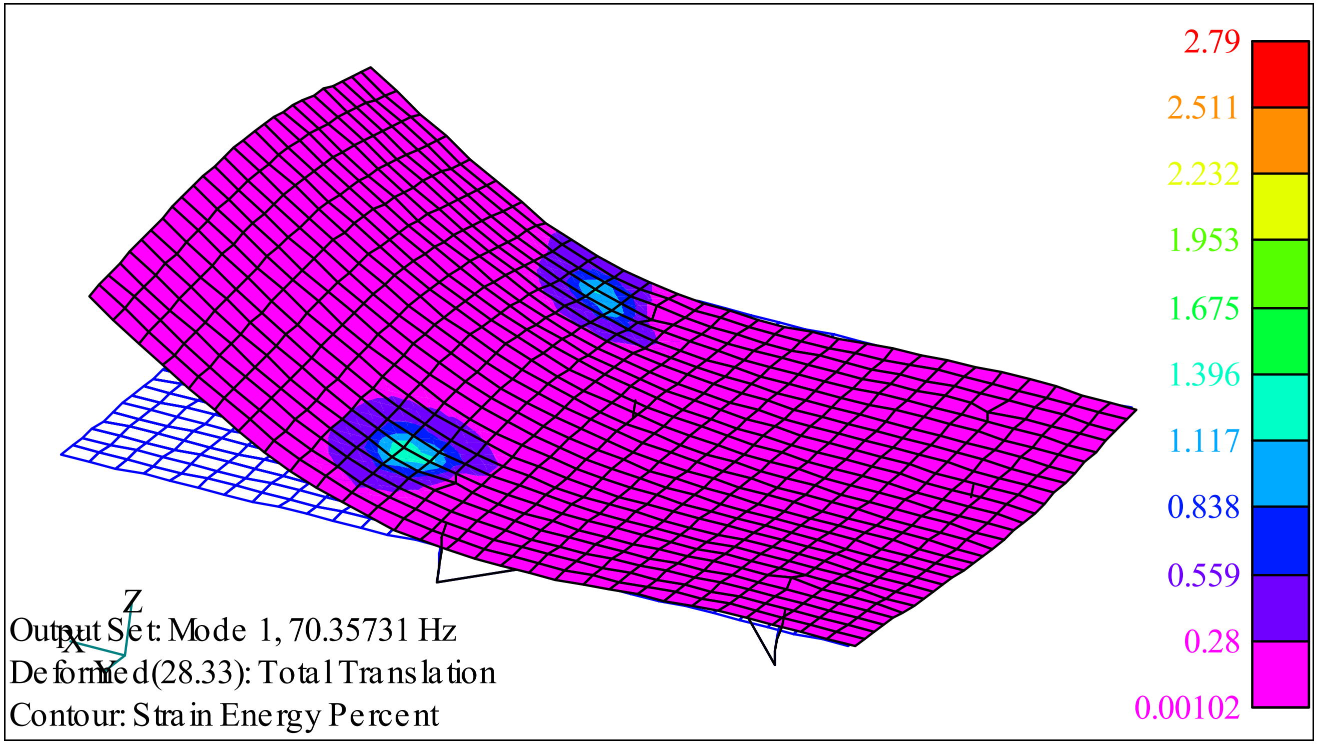
Lateral: 22 G

Sine Burst Tests performed with No structural or functional degradation.

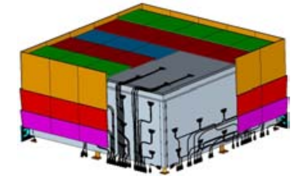
Tile Normal Modes



- Frequency requirement is met.
- Lowest Frequency is 70 Hz for the Side-4 Tiles (with the maximum overhang). Mode shape shown below.
- All other tiles have higher fundamental frequencies.



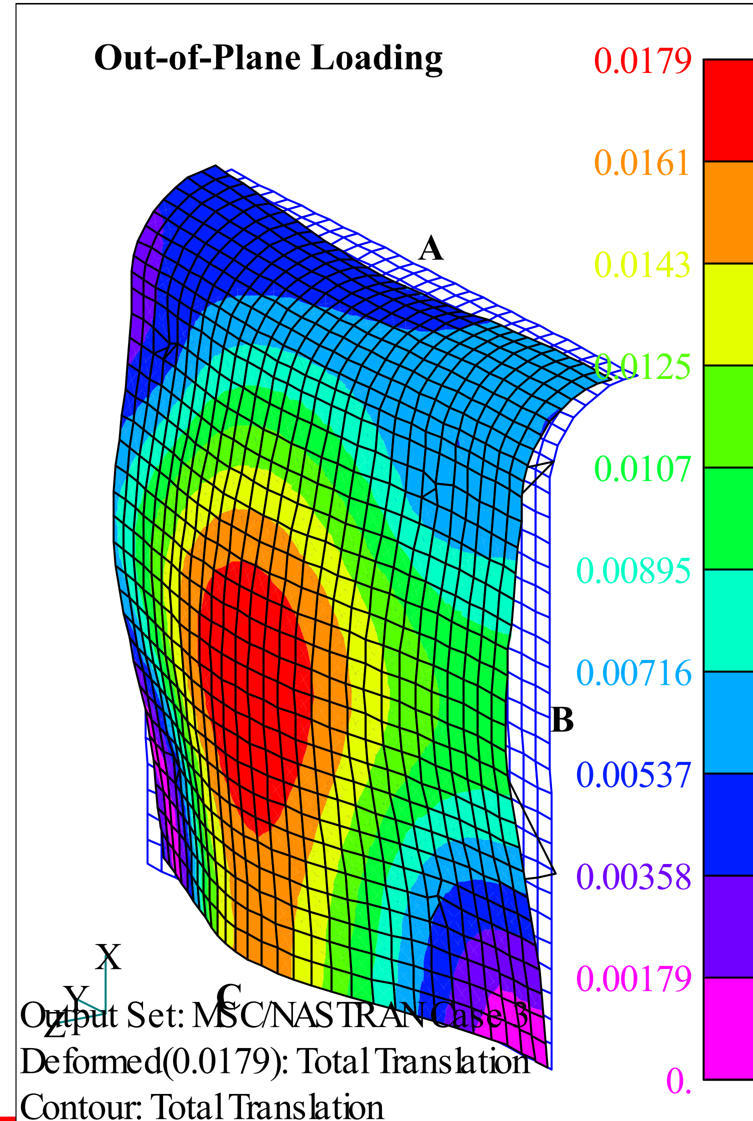
Tile Deformations



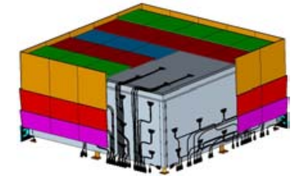
Typical Tile Deflections: Top-3 Tiles

Top-3 Tile Deformations				
under Vibro-Acoustic Loading				
	normal	lateral		
Point	mm	mm		
A	0.1	0.2		
B	0.3	0.2		
C	0.4	0.2		
Deformations are + or -.				
under Thermal Loading				
in-plane deformations				
	-45 C	-25 C	+45 C	
Point	mm	mm	mm	
A	-0.7	-0.5	0.2	
B	-1.0	-0.7	0.3	
C	-0.9	-0.6	0.2	
"-" indicates deformation increases gap.				

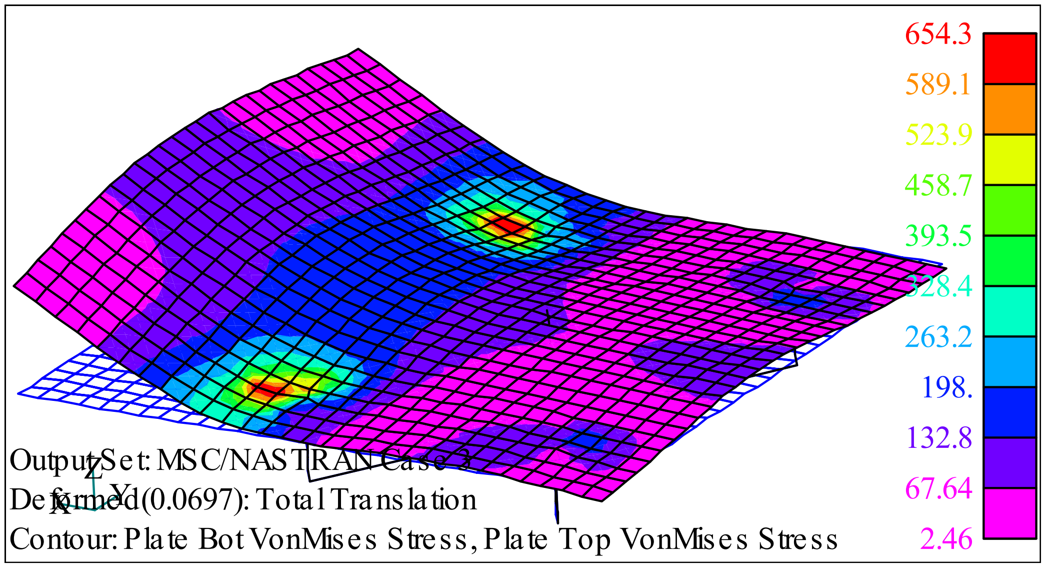
Tile motions caused by ACD Shell flexibility and deformations considered separately.



Tile Stresses

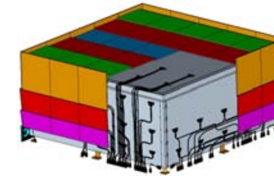


Tile Maximum Bending Stress=660 psi under out-of-plane loading (shown) so MS=4450/(2.6*660)-1= +1.59 OK (Worst Case:Side-4 Tiles)

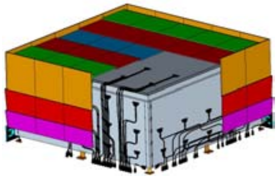


Tile Max Ultimate Compressive Stress under Fastener preload and prying is 3280 psi so MS=4450/3280-1=+0.36 OK.

Conclusions & Remaining Work

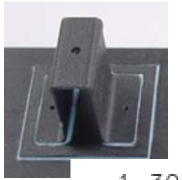


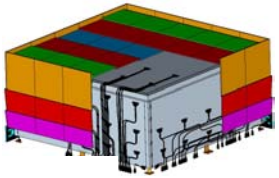
- Graphite Fiber Composite Material Flexures developed to meet the challenging requirements of mounting the ACD Tiles.
- FEA of tiles and detailed FEA of flexures guided the design and final sizing of the flight flexures.
- Prototype Pull tests and Vibration Tests qualified the flexure design. Flexure FEA successfully correlated with test results.
- Tile minimum frequency (70 Hz), structural integrity, and deflection requirements are met.
- Flexure fatigue due to on-orbit thermal cycling is not a real concern owing to the ample static strength margins maintained for the flexures under thermal loads. Any risk will be mitigated by damage tolerance analysis and NDE (Non-Destructive Examination) of the flight flexures.
- Flight drawing release is underway to be followed by fabrication and acceptance testing of the flight flexures and tile assemblies.

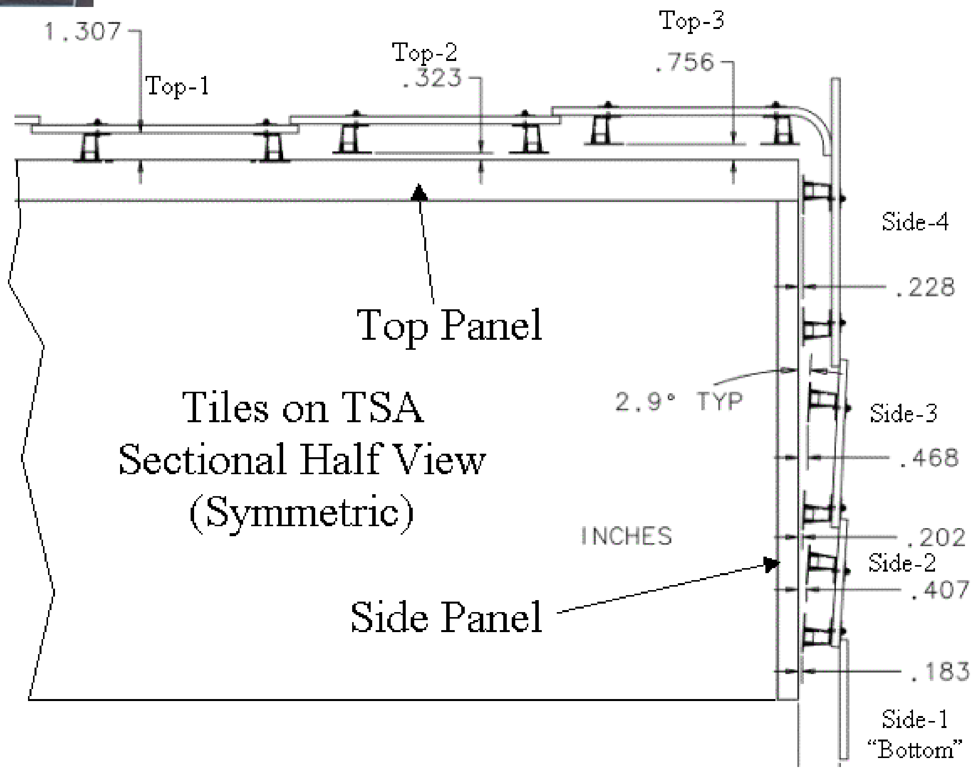


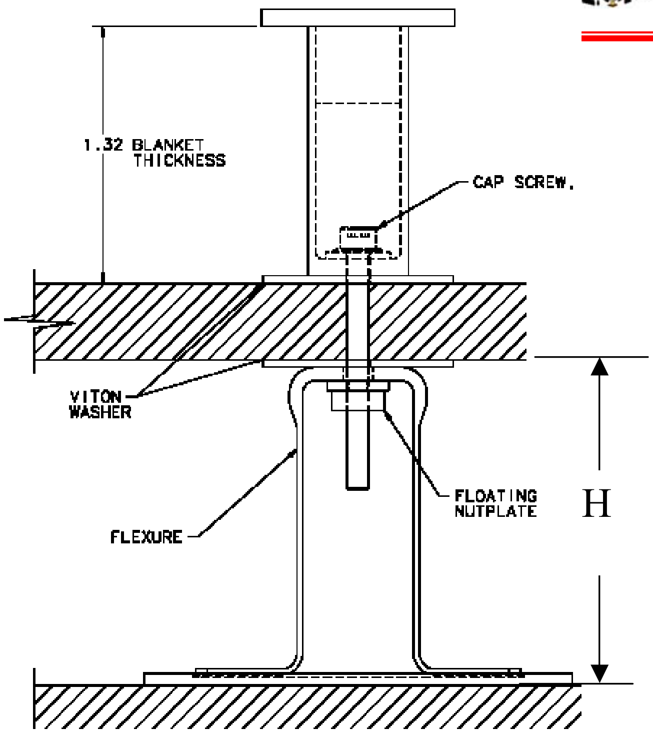
Back-up Slides

TDA-Shell Interface



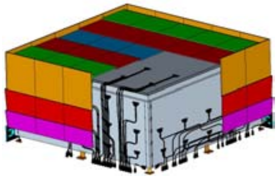




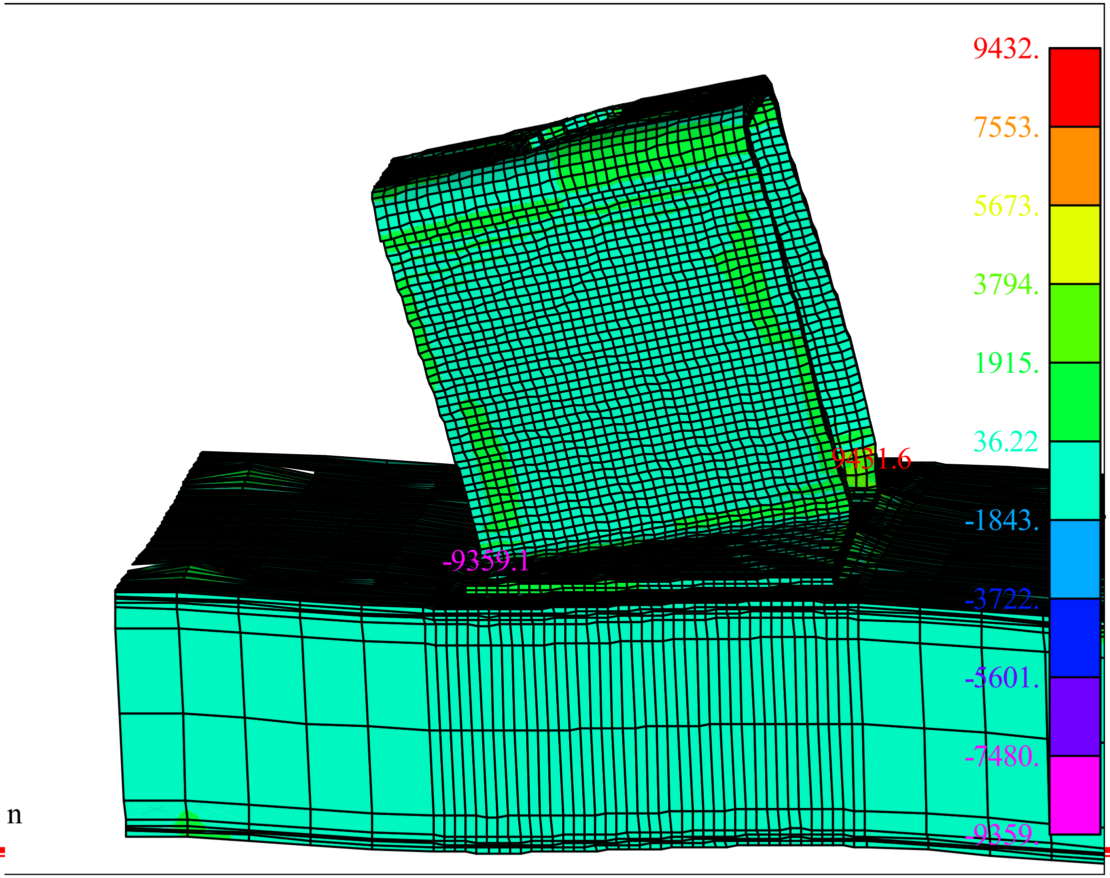


Upper Tile Flexure Heights in inches (4 Different Heights are needed)						
	Top-1	Top-2	Side-4	Side-3	Side-2	Top-3
Panel-Tile Gap,G=	1.307	1.63	1.535	1.775	1.714	2.063
Washer Thickness,W=	0.1	0.1	0.1	0.1	0.1	0.1
Shim thickness, S=	0	0.09	0	0.07	0	0.02
Flexure Height, H=G-W-S=	1.21	1.44	1.44	1.61	1.61	1.94
* Different height Flexures need to be sized by analysis.						

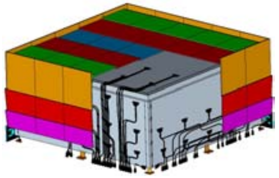
Flexure Stiffness & Strength Correlation under Strong Axis Shear



Under 170 LB strong Axis Shear
Peel stresses exceed 9 ksi to cause failure. Test Failure load was 200 LB. Note that analysis is linear and does not account for local yielding and load redistribution.
Stiffness=170/.0268=6340 Lb/inch (1.5 % greater than measured)

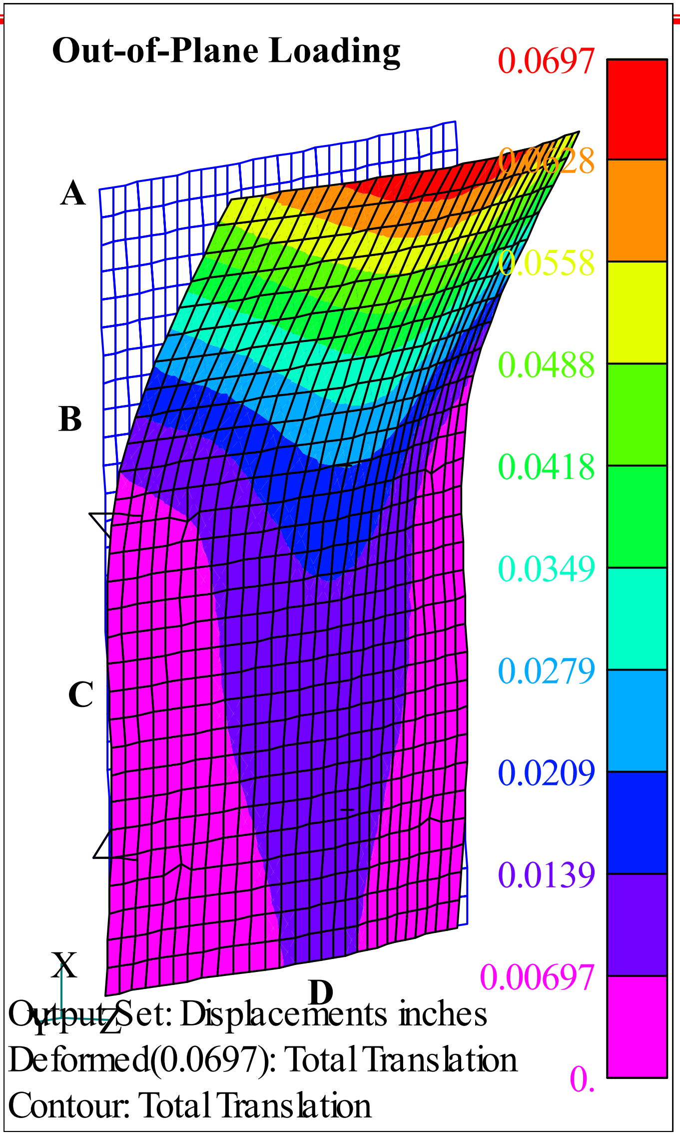


Side-4 Tile Deformations



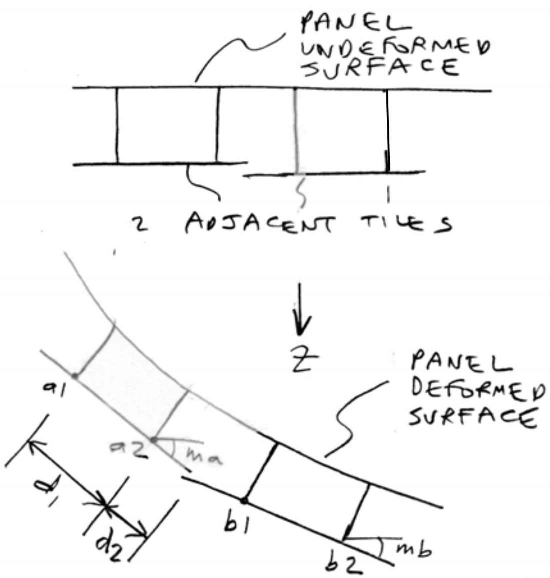
	Side-4 Tile Deformations		
	under Vibro-Acoustic Loading		
	normal	lateral	
Point	mm	mm	
A	1.3	0.1	
B	0.6	0.1	
C	0.1	0.1	
D	0.2	0.1	
	under Thermal Loading		
	-45 C	-25 C	+45 C
Point	mm	mm	mm
A			
B	-0.8	-0.6	0.2
C	-0.8	-0.6	0.2
D	-0.7	-0.5	0.2

Tile motions caused by ACD Shell flexibility and deformations considered separately.

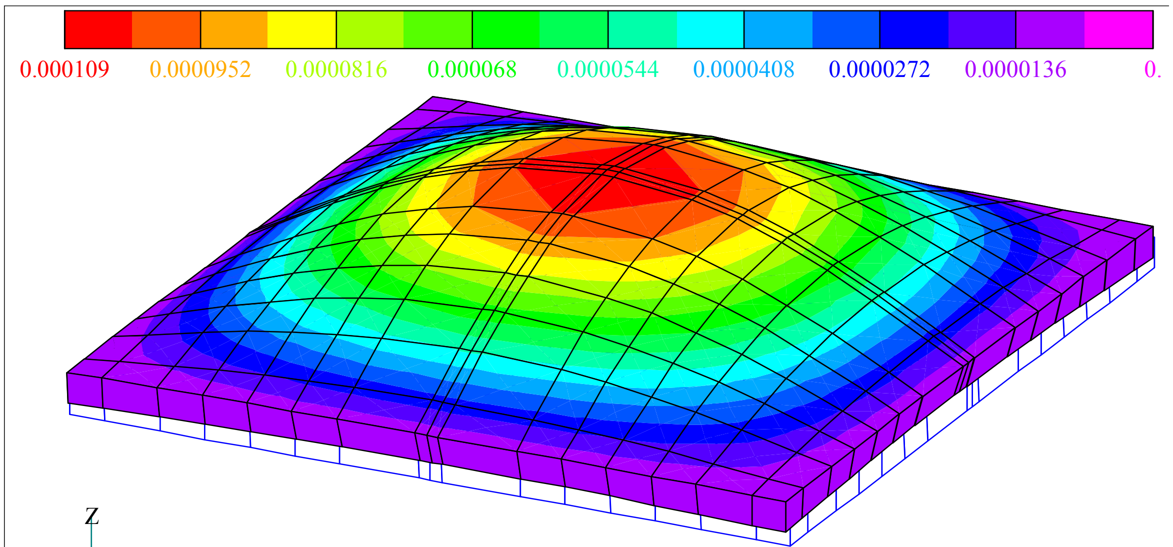


ACD Shell Contribution to Tile Motions

- Panel (ACD Shell) Loading of 6.5 G
- Worst Case Out-of-Plane Tile Deflection is 3 mils due to ACD panel deformations.
- Lateral Deflections of Tiles due to ACD panel deformations are negligible.

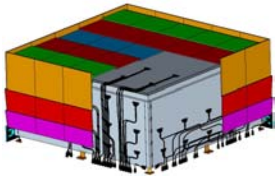


Tile End Deflections due to Panel Deformations	
Panel Deflections	
za1=	8.58E-03
za2=	2.24E-02
zb1=	3.13E-02
zb2=	3.65E-02
Distances on Tile	
d1=	8.40E+00
d2=	2.50E+00
Slopes of Adjacent Tiles	
Slope of Tile a, ma=(za2-za1)/d1=	1.64E-03
Slope of Tile b, mb=(zb2-zb1)/d1=	6.19E-04
Deflection of Tile Ends	
zea=za2+ma*d2=	2.65E-02
zeb=zb1-mb*d2=	2.98E-02
Net Approach of Tile Ends	
ze=abs(zea-zeb)=	3.29E-03



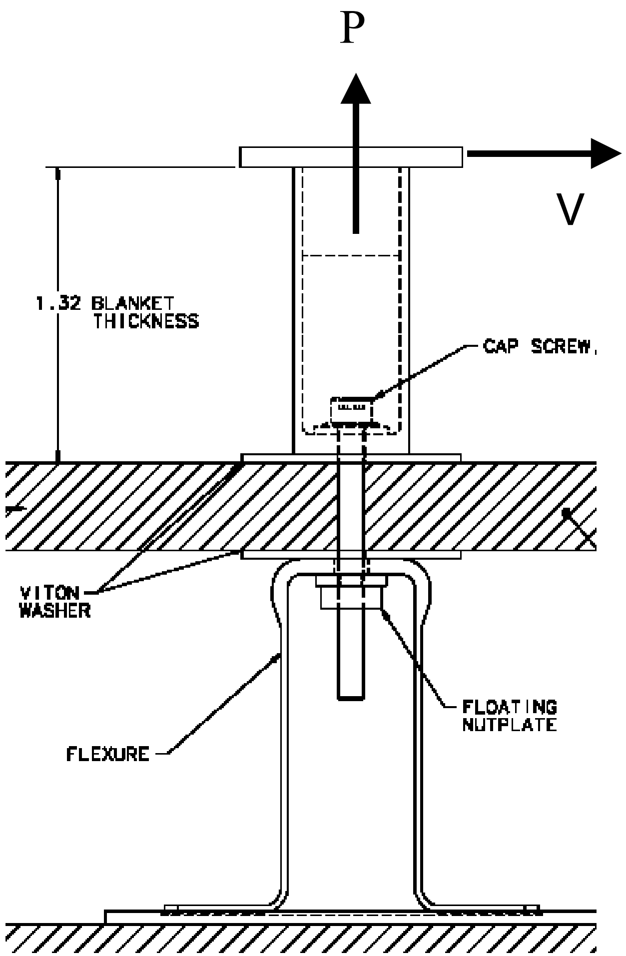
Top Panel under out-of-plane Loading

Blanket Stand-off Stress Analysis

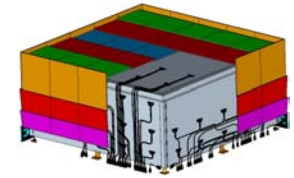


Cantilevered Bending Stresses

Case:		Lateral	Axial	Handling
Cantilevered Length, L=	inch	1.32	1.32	1.4
Section Modulus, S=I/c=	in^3	0.0044	0.0044	0.0044
Applied Transverse Load, V=	LB	5	0	5
Applied Axial Load, P=	LB	0	11	0
Max End Moment, M=V*L/2=	in.LB	3.3	0	3.5
Max Bend Stress, Sb=V*L/S=	psi	1500	0	1590
Flexural Shear Stress, Ss=Fs*V/A=	psi	219	0	219
Axial Stress, Sa=P/A=	psi	0	241	0
Max Stress,Sm=Sa+Sb=	psi	1500	241	1590
Material Strength, Ftu=	psi	16500	16500	16500
Safety Factor, SF=	-	2.6	2.6	2.6
MS=Ftu/(SF*Sb)-1=	-	3.23	Large	2.99
Modulus Of Elasticity, E=	psi	5.0E+05	5.0E+05	5.0E+05
Buckling Load=PI^2*E*I/4/L^2=	LB	701	701	623
Round Tube OD=	inch	0.45	0.45	0.45
ID=	inch	0.38	0.38	0.38
wall thickness, tw=(OD-ID)/2=	inch	0.035	0.035	0.035
Area, A=PI*(OD^2-ID^2)/4=	in^2	0.045632	0.045632	0.045632
Moment of Inertia, I=PI*(OD^4-ID^4)/64=	in^4	0.0010	0.0010	0.0010
Section Modulus, S=I/c=I/(OD/2)=	in^3	0.0044	0.0044	0.0044
Shear Shape Factor, Fs=	-	2.00	2.00	2.00

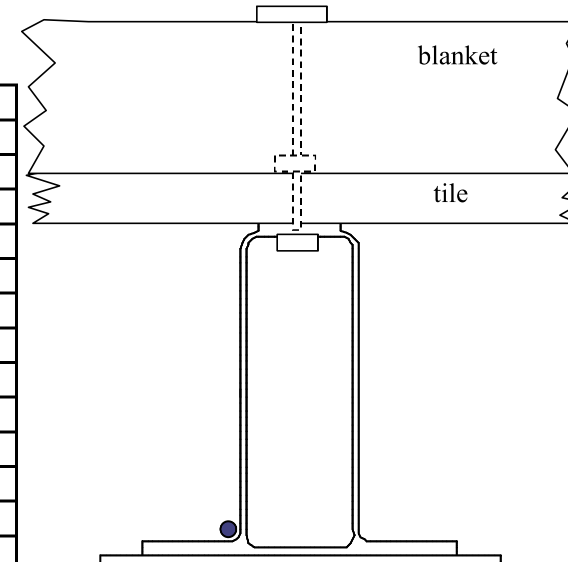


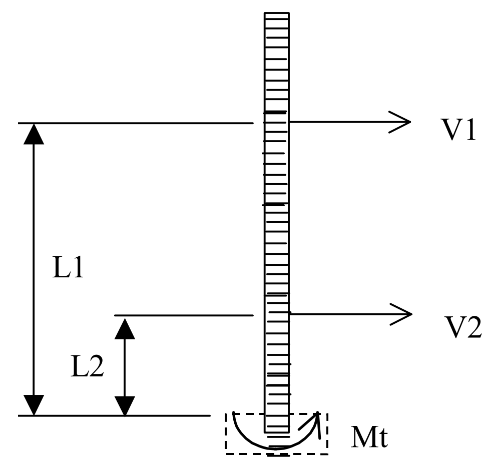
Tile Fastener Stress Analysis



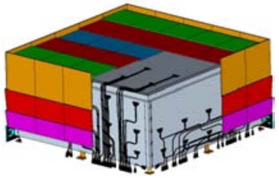
Bolt under Tension+Shear+Bending

Case		Lat-1	Lat-2	Handling
Bolt Major Diameter, dm=	inch	0.112	0.112	0.112
Number of Threads per inch, 1/p=	-	40	40	40
Pitch Diameter, dp=dm-.6495*p=	inch	0.096	0.096	0.096
Minor Diameter,dr=dm-1.2990p=	inch	0.080	0.080	0.080
Tensile Diameter,dt=(dp+dr)/2=	inch	0.088	0.088	0.088
Tensile Area, At=PI*dt^2/4=	inch^2	0.006	0.006	0.006
Diameter for MOI, di=		0.088	0.088	0.088
Tensile MOI=pi()*di^4/64=	inch^4	2.90E-06	2.90E-06	2.90E-06
Tensile SM=It/(di/2)=	inch^3	6.61E-05	6.61E-05	6.61E-05
Applied Tension, P=	LB	28.0	45.0	53.0
Applied Shear-1, V1=	LB	5.0	3.8	5.0
Distance of V1 to base, L1=	inch	0.45	0.45	0.45
Applied Shear-2, V2=	LB	17	13	0
Distance of V2 to base, L2=	inch	0.05	0.05	0.05
Bolt Tensile Strength, Ftu=	psi	160,000	160,000	160,000
Bolt Yield Strength, Fty=	psi	120,000	120,000	120,000
Bolt Preload Stress/Fty=	-	0.35	0.35	0.35
Bolt Preload Stress, Sp=	psi	42000	42000	42000
Bolt Preload, Po=At*Fps=	psi	253	253	253
Torque, T=0.2*Po*dm=	in.LB	6	6	6
Moment Distribution Factor, fM=	-	0.70	0.70	0.70
Induced Moment, Mt=fM(V1*L1+V2*L2)=	in.LB	2.2	1.7	1.6
stress due to P, Sp=P/At=	psi	4641.2	7459.0	8785.0
Moment Stress, Sm=Mt/SM=	psi	32832	24995	23830
SF=	-	2.6	2.6	2.6
Total Normal Stress, St=Sm+Sp=	psi	139430	126380	126798
Bolt MS=Ftu/St-1=	-	0.15	0.27	0.26

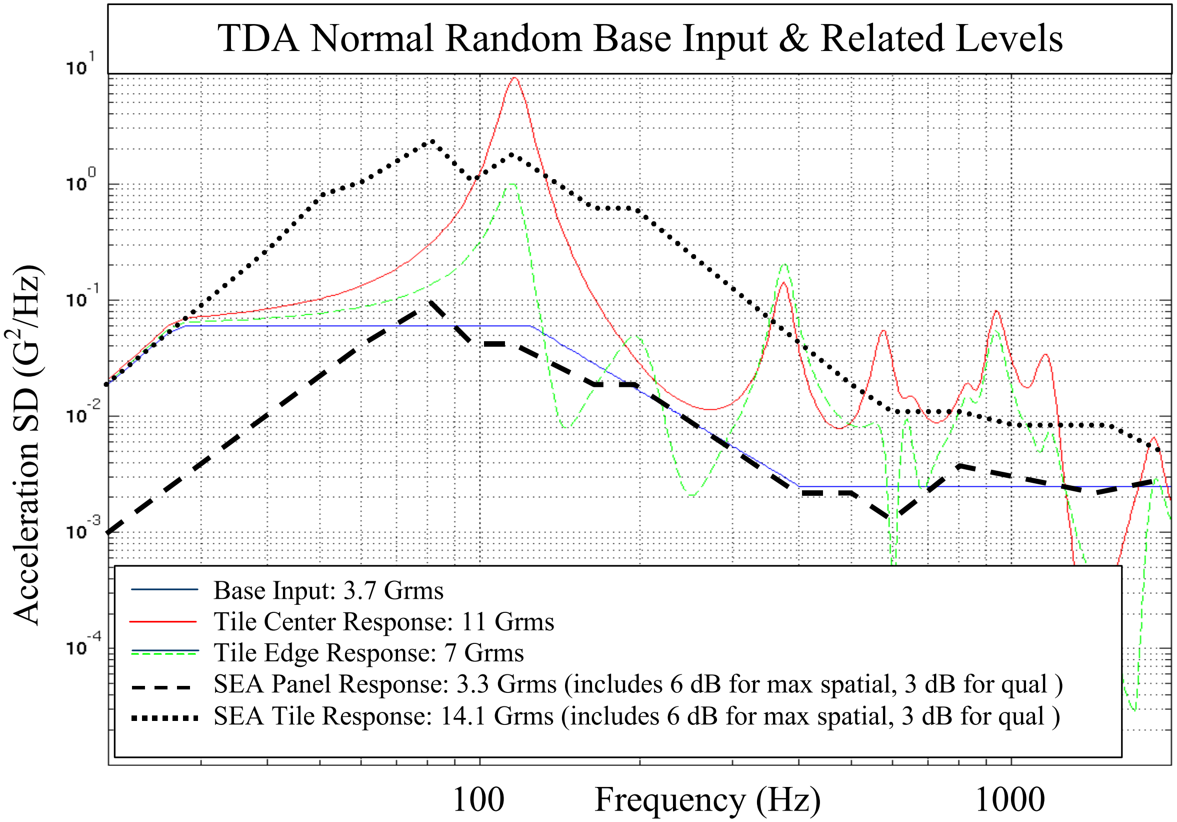




Tile Detector Normal Random Vibe Level



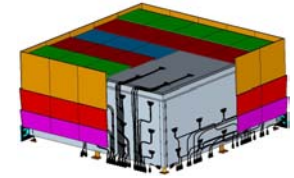
- SEA Panel and Tile results are used to derive TDT Random Vibe Levels. SEA results are scaled-up by 6 dB to envelope max spatial response and by 3 dB to reach qual levels.



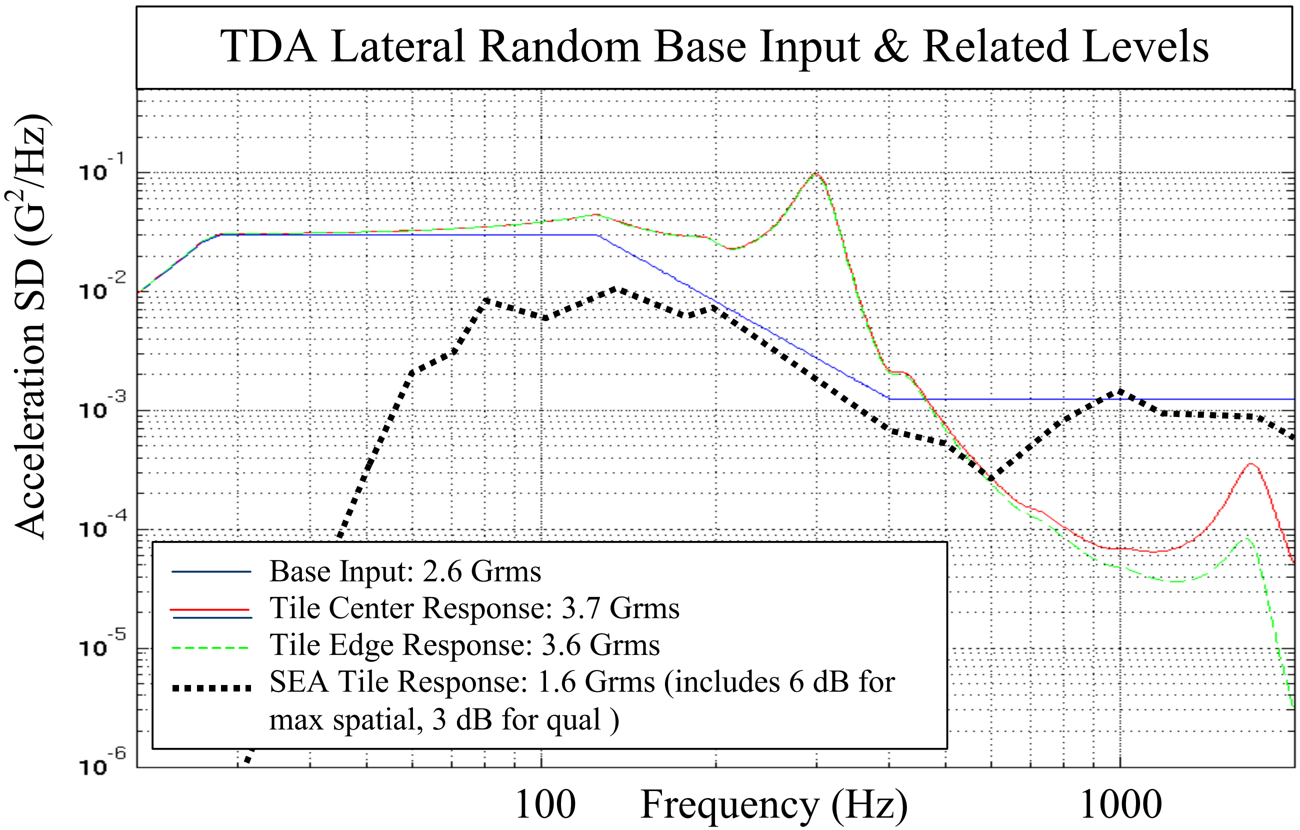
- Normal Random Base input was selected to envelope the scaled SEA panel response. The envelope is expanded below the tile fundamental frequency to match the scaled TDA rigid SEA response.

- Predicted and measured tile responses from random base-drive analysis roughly approximate the scaled SEA tile response, indicating that the selected base input is sufficiently high.

Tile Detector Lateral Random Vibe Level



- Lateral Random Base input profile is selected to be 3dB less than the normal base input. This approach is conservative because tile Lateral SEA response is much less than its normal response under acoustic loading. This approach was taken not to rely heavily on SEA lateral predictions, which may not be as reliable as its out-of-plane predictions.



- Lateral base input envelopes the SEA scaled tile response. Predicted and measured tile responses under random base shake significantly exceed the SEA scaled lateral response under 500 Hz.